Nuclear Energy's Future?

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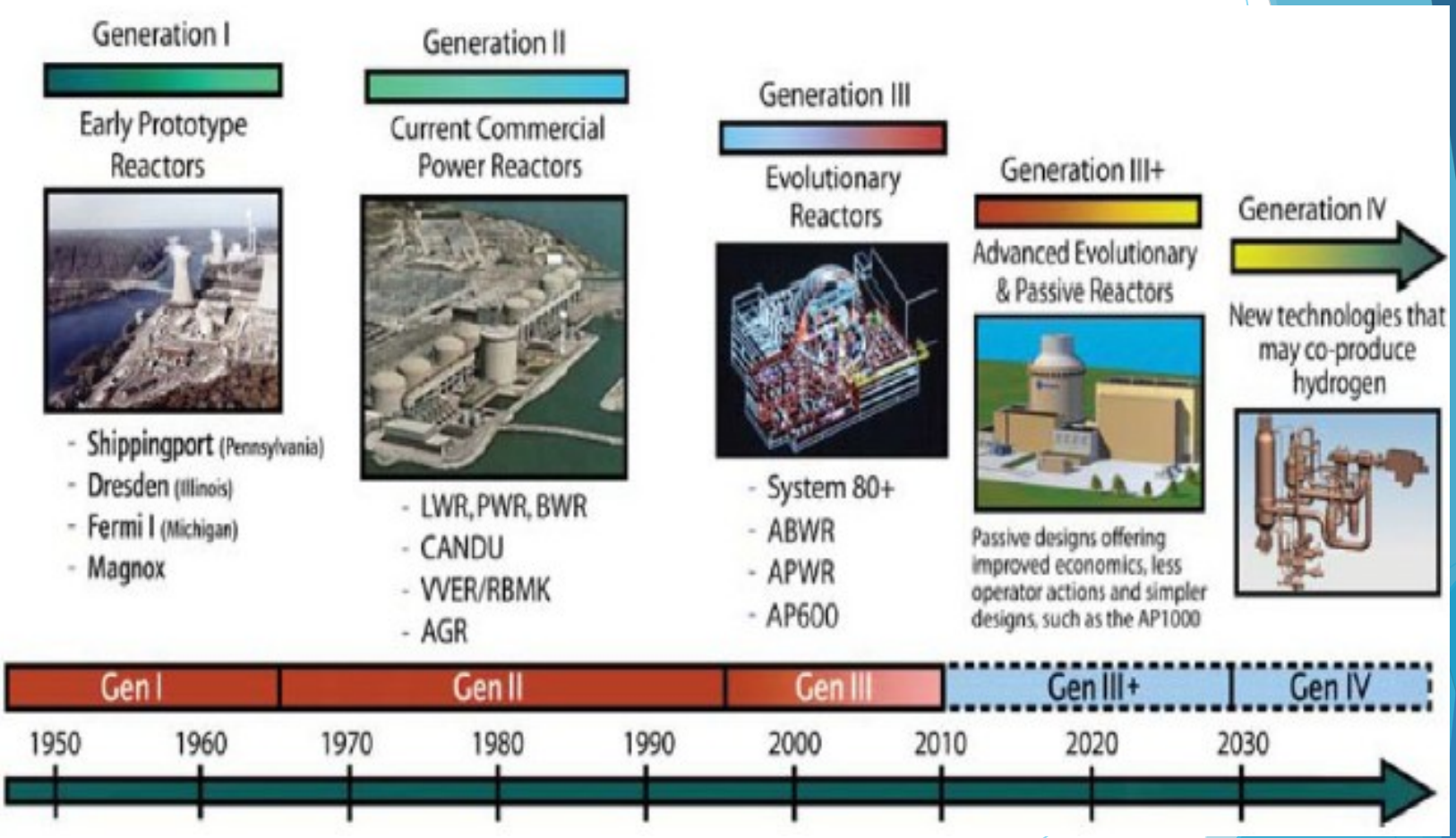
Nuclear Reactor Evolution



Generation I Reactors

- U.S. Generation I reactors mostly experimental/test reactors constructed after World War II; included prototype BWR (Dresden) and PWR (Shippingport) reactors and demonstration breeder reactor (Fermi I)
- Magnox was British natural uranium, graphite-moderated, CO_2-cooled prototype gas-cooled reactor (GCR)
- None of Generation I reactors still operating; most don’t exist anymore (Experimental Breeder Reactor I in Idaho is National Historic Landmark open for public tours)

Generation II Reactors

- 93 Generation II light-water reactors generating electricity in U.S. (as of 2025)
  - Last Gen II reactor purchased in 1978
  - Last Gen II reactor construction completed in 1990s
- CANDU is Canadian natural uranium, heavy water-moderated reactor
- VVER and RBMK are Russian water-cooled reactors
- AGR is British Advanced Gas-cooled Reactor

Generation III Reactors

- Only few Generation III reactors operating or under construction; none in U.S.
- Generation III+ reactors currently generating electricity in China
- Two Generation III+ reactors (Vogtle Units 3 and 4) operating in U.S.

Generation III+ Reactors

Characteristics include:

- Simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets
- Passive or inherent safety features require no active controls or immediate operator intervention to mitigate accidents in event of malfunction (e.g., rely on gravity, natural convection and resistance of materials to high temperatures)
- Reduced possibility of core melt accidents
- Higher fuel burnup to reduce fuel loading and waste generation
- Higher availability and longer operating life - typically 60 years
- Reduced generation of radioactive waste
- 50 - 300 MWe output (40,000 – 240,000 homes)

Westinghouse AP-1000 Nuclear Power Plant – Vogtle Units 3 & 4

Gen II vs. Gen III+ Reactor Safety

- Generation II nuclear power plants rely on active safety measures for mitigating reactor accidents
  - Electrical power needed for motor-operated pumps and valves, instrumentation and control hardware
  - Early reactor operator intervention necessary
- Generation III+ nuclear power plants rely on passive safety measures for mitigating accidents
  - Plant designs incorporate gravity, natural circulation, high temperature resistance of materials for accident mitigation
  - No operator intervention required to mitigate accidents

Generation IV Reactors

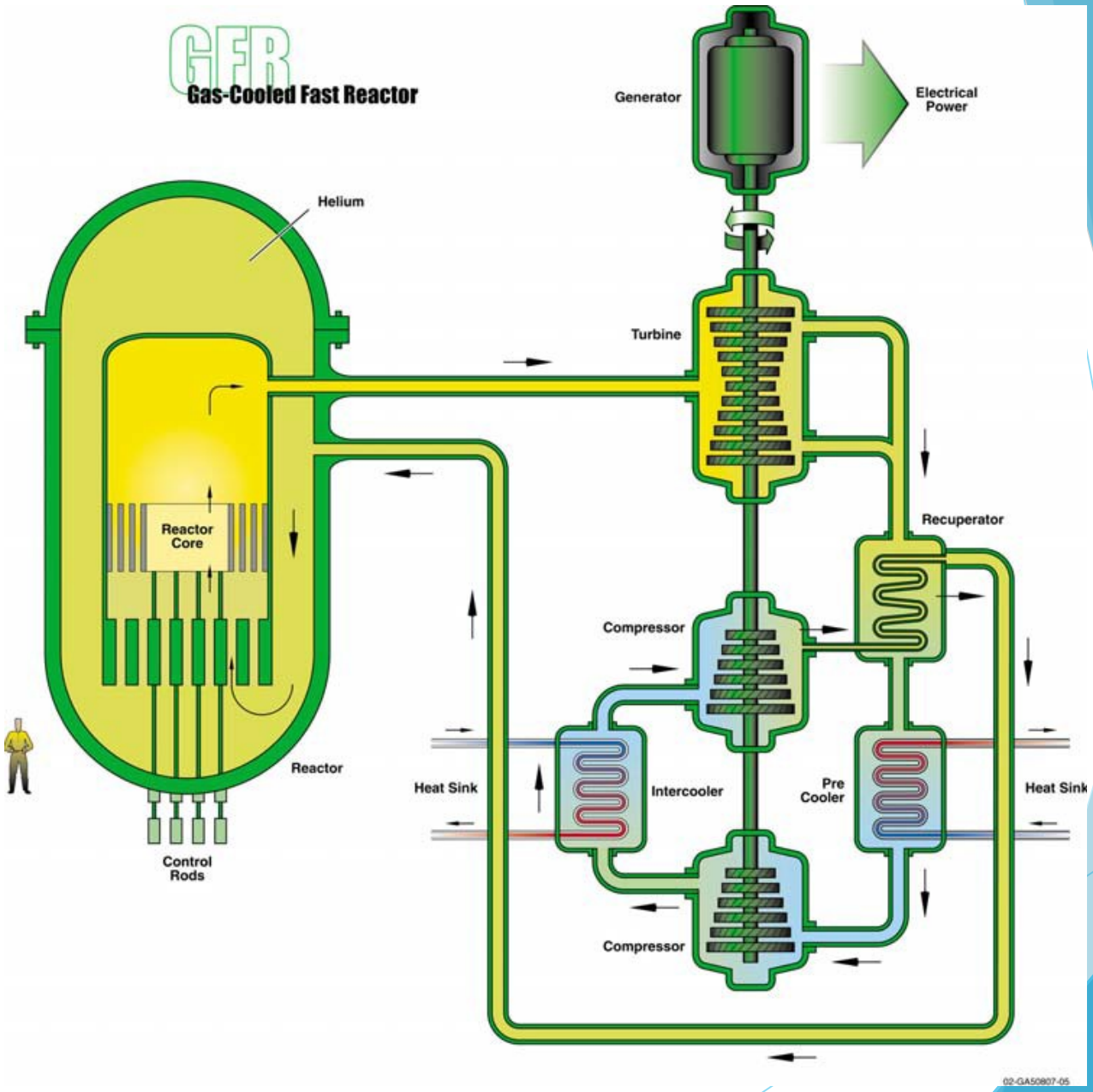
Next generation reactor concepts designed to address world energy needs into the future with attributes such as:

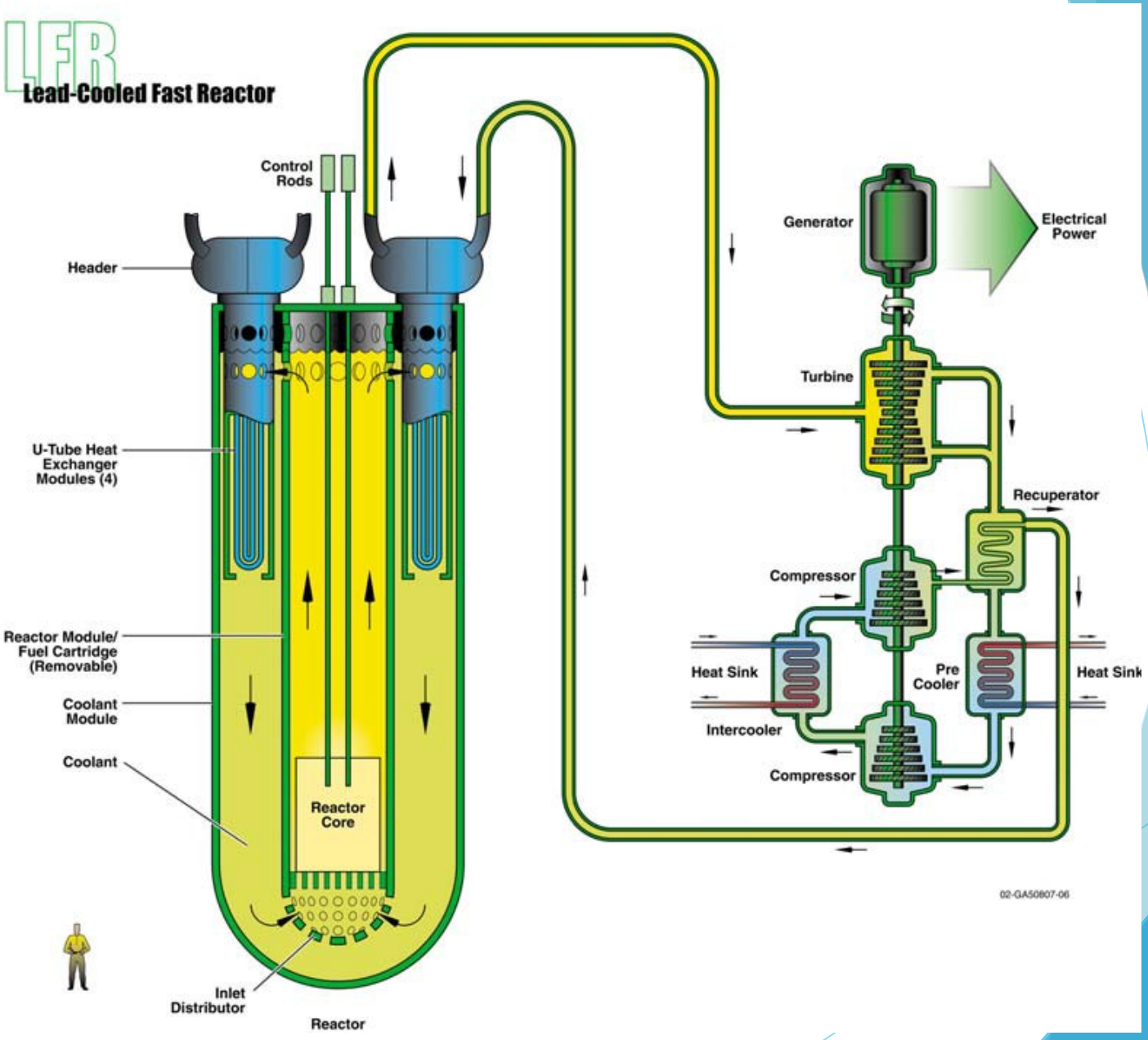
- More efficient utilization of uranium (many can employ depleted uranium or used fuel from current reactors)
- Transmutation of long-lived nuclear waste to isotopes with shorter half-lives
- Generation of hydrogen for transportation and providing other non-electric energy needs (e.g., desalination)
- Inherent safety and easy of operation
- Inherent nuclear weapon proliferation resistance
- Clear cost advantage over other forms of electricity generation
- Financial risk no greater than other forms of electricity generation

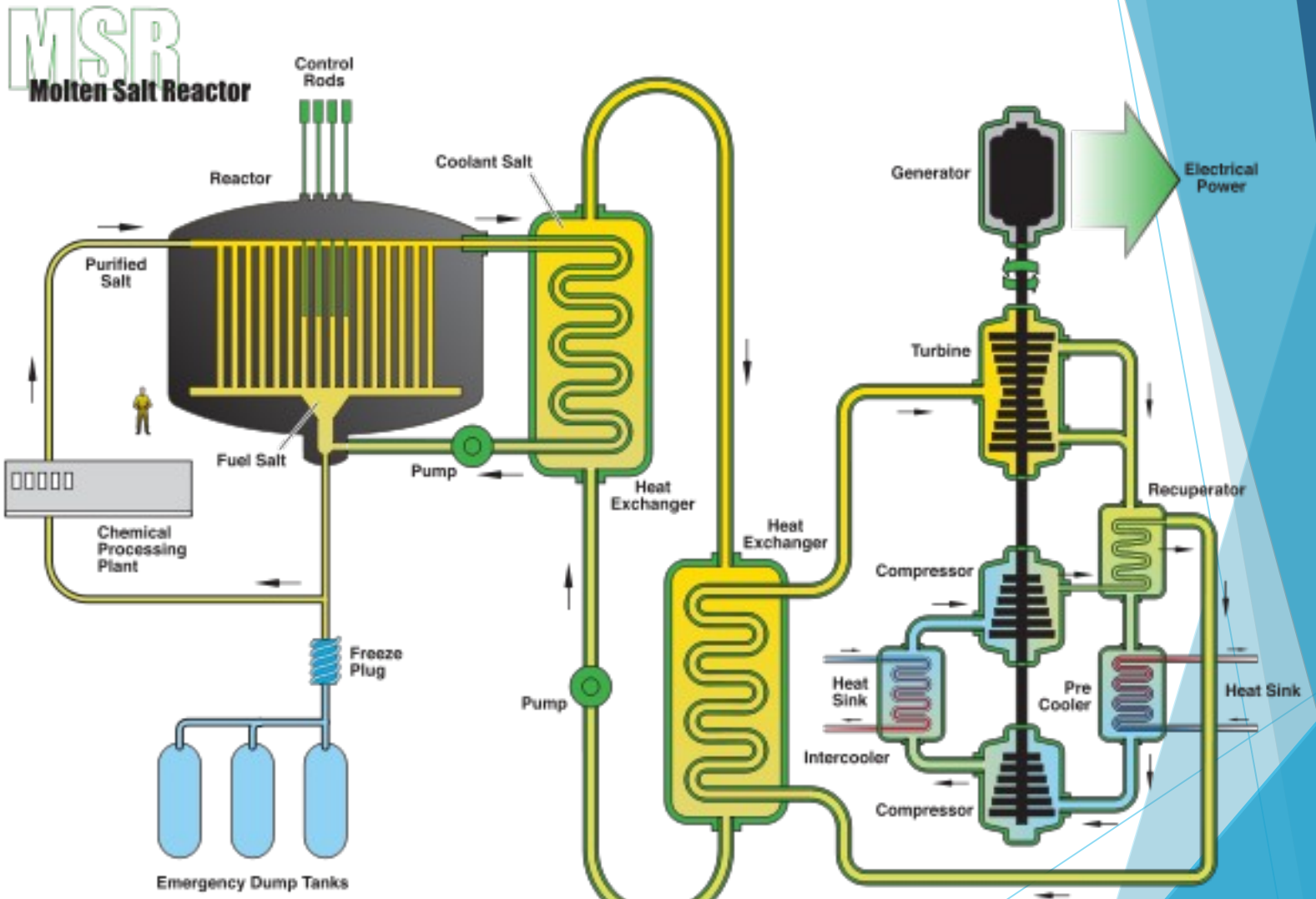
Gen IV Reactor Systems Under Development

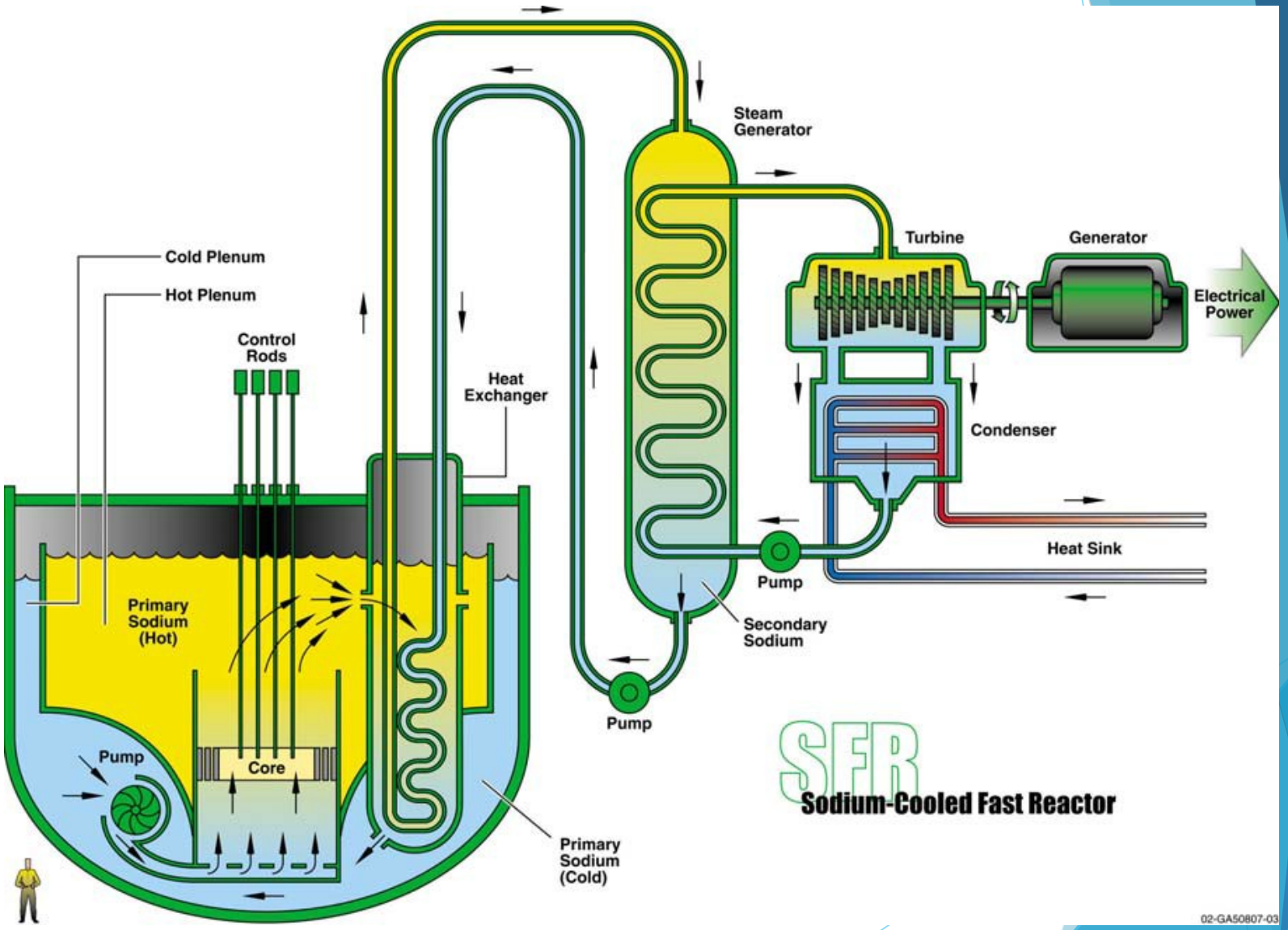
Reactor Type	Neutron Spectrum (fast/ thermal)	Coolant	Temp. (º C)	Press.*	Fuel	Fuel Cycle	Size(s) (MWe)	Uses
Gas-cooled Fast Reactor	Fast	Helium	850	High	U-238**	Closed, on site	1200	Electricity & Hydrogen
Lead-cooled Fast Reactor	Fast	Lead or Pb-Bi	480-800	Low	U-238**	Closed, regional	20-180*** 300-1200 600-1000	Electricity & Hydrogen
Molten Salt Fast Reactor	Fast	Fluoride salts	700-800	Low	UF in salt	Closed	1000	Electricity & Hydrogen
Molten Salt Reactor – Advanced High-temp. Reactor	Thermal	Fluoride salts	750-1000		UO_2 particles in prism	Open	1000-1500	Hydrogen
Sodium-cooled Fast Reactor	Fast	Sodium	550	Low	U-238 & MOX	Closed	30-150 300-1500 1000-2000	Electricity
Supercritical Water-cooled Reactor	Thermal or Fast	Water	510-625	Very high	UO_2	Open (thermal) Closed (fast)	300-700 1000-1500	Electricity
Very High Temp. Gas Reactor	Thermal	Helium	900-1000	High	UO_2 prism or pebbles	Open	250-300	Electricity & Hydrogen

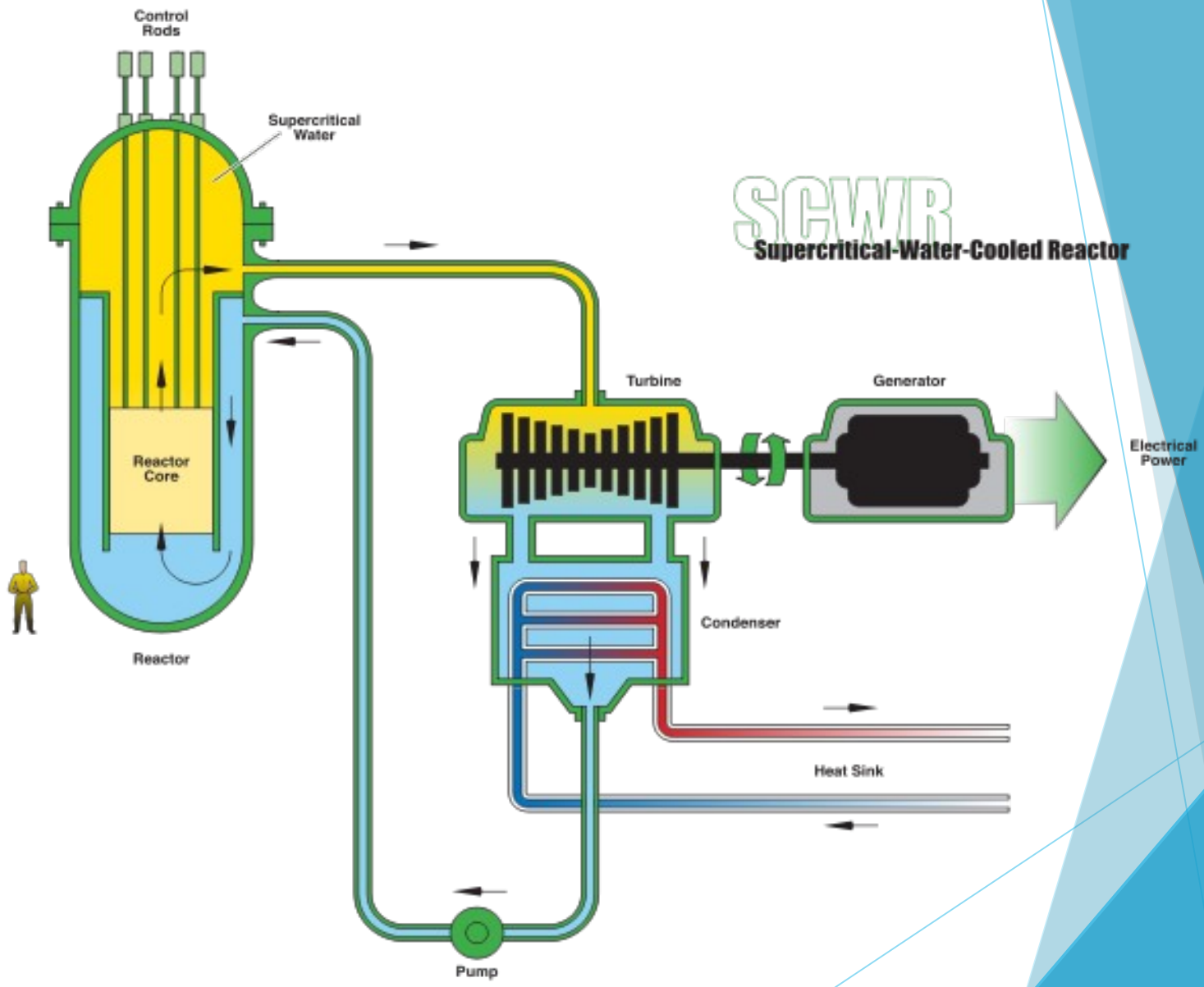
* High = 1000 – 2000 psi
** With some U-235 or Pu-239
*** “Battery” model with long core cassette life (15-20 years) or replaceable reactor module

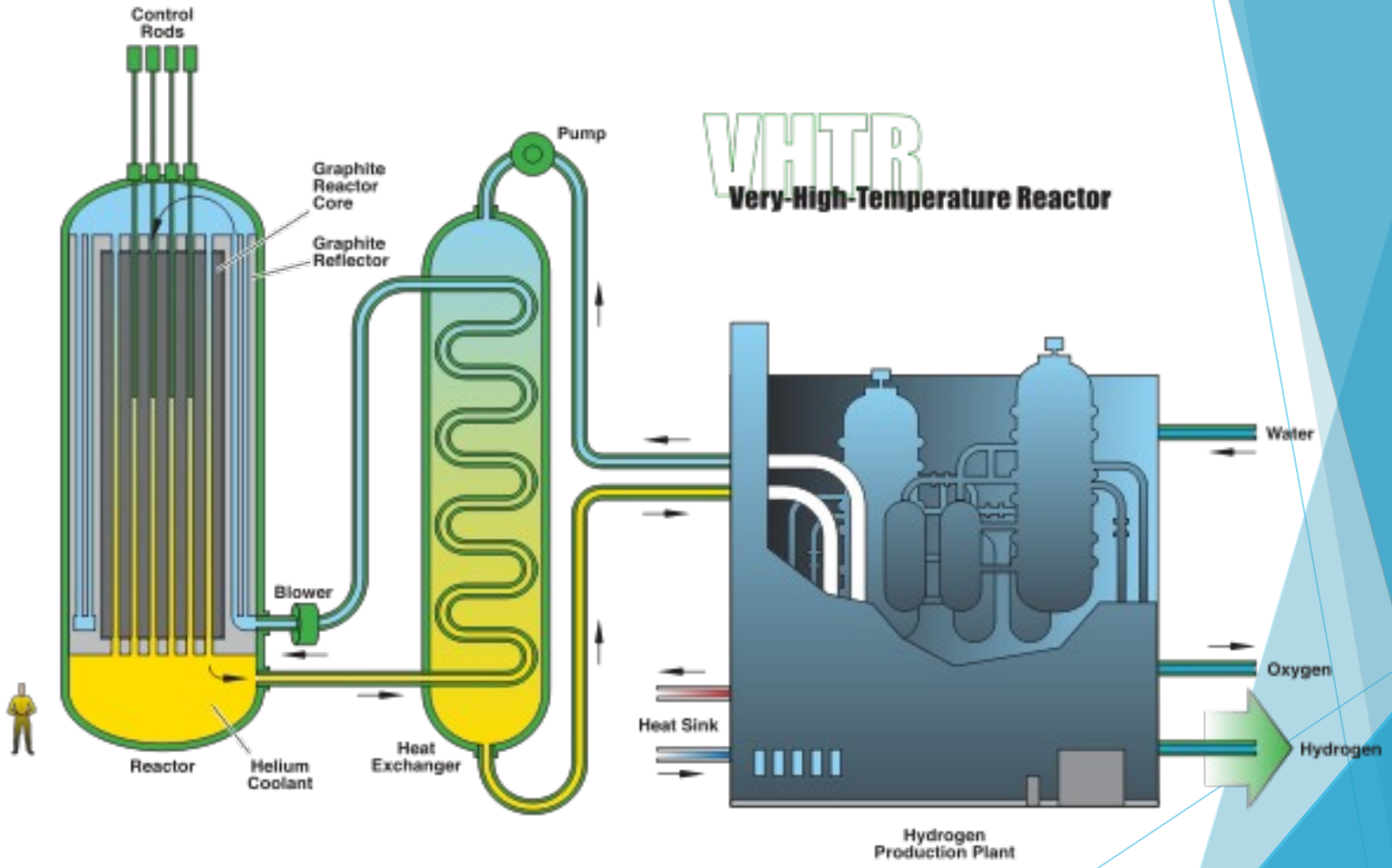

GFR
Gas-Cooled Fast Reactor
Generator
Electrical Power
Helium
Turbine
Reactor Core
Recuperator
Compressor
Reactor
Heat Sink
Intercooler
Pre Cooler
Heat Sink
Control Rods
Compressor
02-GA50807-05


LFR
Lead-Cooled Fast Reactor
Control Rods
Header
U-Tube Heat Exchanger Modules (4)
Reactor Module/ Fuel Cartridge (Removable)
Coolant Module
Coolant
Reactor Core
Inlet Distributor
Reactor
Generator
Electrical Power
Turbine
Recuperator
Compressor
Heat Sink
Pre Cooler
Heat Sink
Intercooler
Compressor
02-GA50807-06


MSR
Molten Salt Reactor
Control Rods
Reactor
Coolant Salt
Purified Salt
Fuel Salt
Pump
Heat Exchanger
Chemical Processing Plant
Freeze Plug
Emergency Dump Tanks
Pump
Heat Exchanger
Generator
Electrical Power
Turbine
Recuperator
Compressor
Heat Sink
Pre Cooler
Heat Sink
Intercooler
Compressor


Steam Generator
Turbine
Generator
Electrical Power
Cold Plenum
Hot Plenum
Control Rods
Heat Exchanger
Condenser
Heat Sink
Pump
Secondary Sodium
Primary Sodium (Hot)
Pump
Core
Primary Sodium (Cold)
SFR
Sodium-Cooled Fast Reactor
02-GA50807-03


Control Rods
Supercritical Water
SCWR
Supercritical-Water-Cooled Reactor
Turbine
Generator
Electrical Power
Reactor Core
Condenser
Reactor
Heat Sink
Pump


VHTR
Very-High-Temperature Reactor
Control Rods
Graphite Reactor Core
Graphite Reflector
Pump
Blower
Reactor
Helium Coolant
Heat Exchanger
Heat Sink
Water
Oxygen
Hydrogen
Hydrogen Production Plant

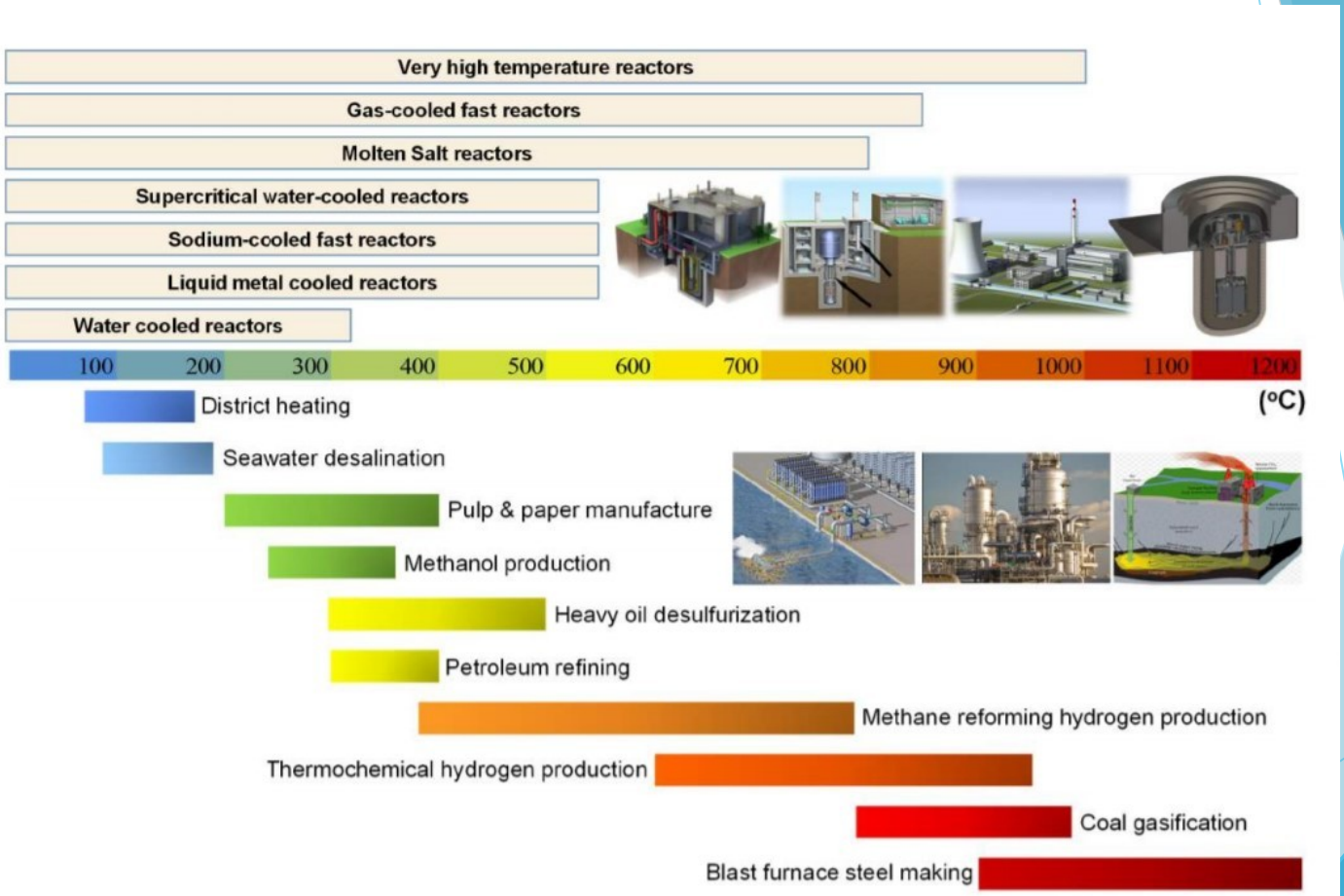
Small Modular Reactors

Small Modular Reactors

Characteristics include:

- Modular construction (factory-built, less onsite construction)
- Lower capital investment
- Siting flexibility
- Increased nuclear materials security
- Load-following designs (electricity production adjusts to demand)
- Longer fuel lifecycles (some designs require no refueling)
- Passive safety features (depend only on laws of physics)

SMR Designs for Non-Electric Applications



Some Small Modular Reactor Concepts

Name/Type	MWe	Vendor	Design Feature
BWRX-300/BWR	300	General Electric-Hitachi	Passive safety systems; natural circulation cooling
VOYGR/PWR	50-300	NuScale Power, Inc.	Integral SGs; natural circulation cooling
PRISM/Liquid Metal	300	General Electric-Hitachi	Pool-type; passive safety systems
4S/Liquid Metal	10-50	Toshiba-Westinghouse	Pool-type; load-following; 30-year core life
Molten salt	150	Kairos Power, LLC	Pebble-type, TRISO HALEU fuel
Xe-100/Helium-cooled	80	X-energy	Pebble bed HTGR; TRISO HALEU fuel

Micro-reactors

Micro-reactors

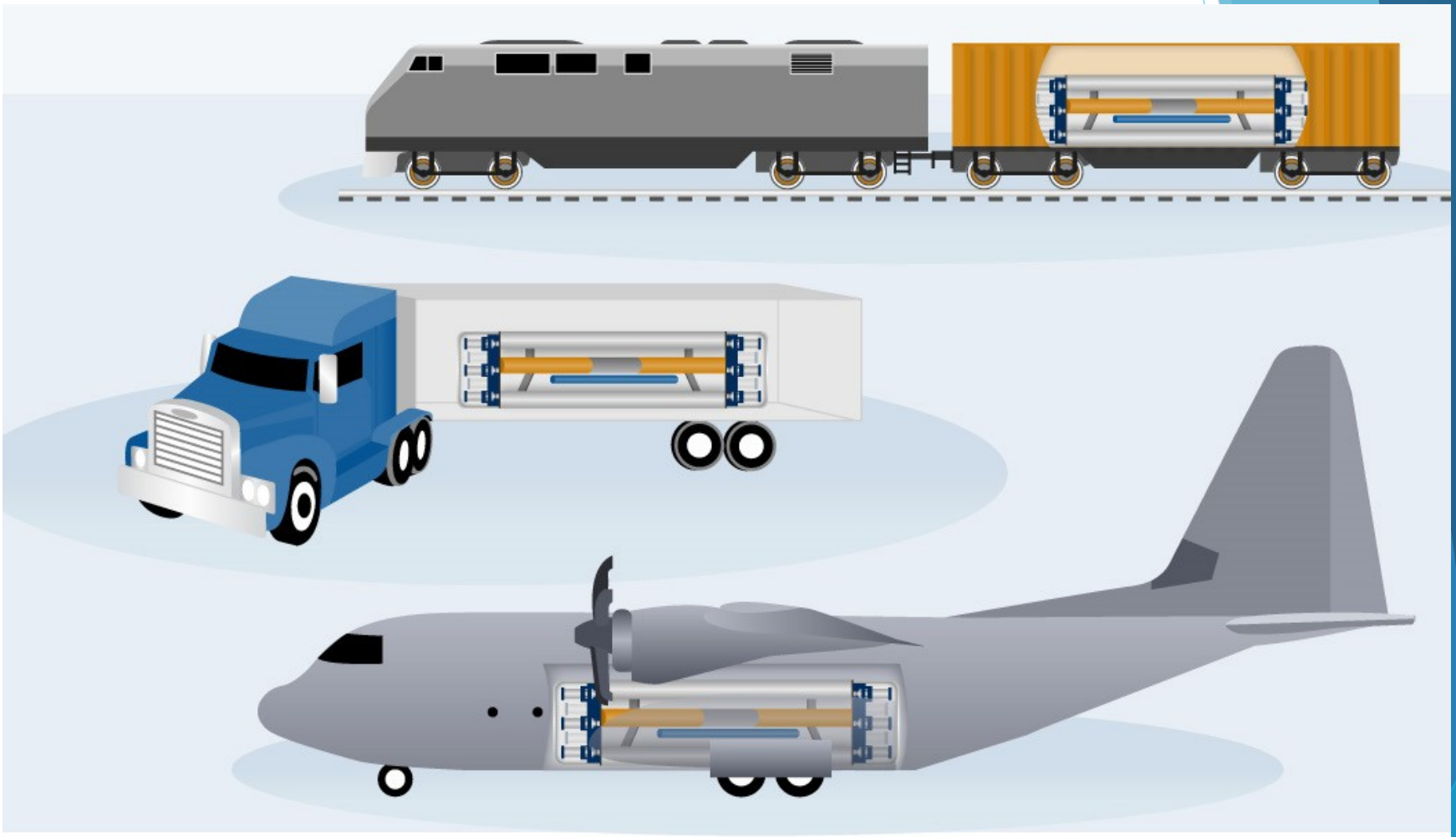
Characteristics include:

- Modular construction (factory-built, less onsite construction)
- Portable (most can be hauled by semi-tractor-trailer, shipped
  by train, or flown by cargo plane)
- Easily scalable (“right-sizing” for particular siting needs)
- Can be designed to produce process heat
- Self-regulating with high degree of safety (depend only on laws of physics)
- Reliable and resilient sources of demand-driven power
- Operate for sustained periods of time without need for refueling

Some Micro-Reactor Concepts

Name/Type	MWe	Vendor	Design Feature
e-Vinci	5	Westinghouse	Passive heat pipe technology, TRISO fuel
Antares R1	0.2-0.3	Antares	Sodium heat pipes, TRISO fuel
Kaleidos	1.2	Radiant	High-temperature gas-cooled
Marvel	10	Aalo Atomics	Sodium-cooled, UZrH fuel
Ward 250	30	Valar Atomics	High-temperature gas-cooled, TRISO fuel
Space Micro-Reactor Concept		Rolls-Royce	Commercial, defense, and space applications
Xe-Mobile	1-5	X-energy	TRISO fuel, multiple voltage outputs

Micro-reactor Portability



Source: GAO. | GAO-20-380SP

Micro-reactor Issues

Micro-reactors struggle to scale down due to unavoidable inherent costs associated with

- radiation shielding
- higher surface-area-to-reactor core-volume requiring more expensive fuel
- complex operations and maintenance (require specialized personnel, even for routine tasks)
- used nuclear fuel handling
- nuclear facility licensing and regulation (micro-reactors are “large civil and regulatory frameworks wrapped around tiny cores”)

SMR and Micro-reactor Obstacles

- Atrophied nuclear industry supply chains
  - American nuclear startup companies operating in vacuum left by collapse of U.S. nuclear industrial base; i.e., deterioration of robust ecosystem of designers, fabricators, metallurgists, machinists, test facilities, and institutions to produce necessary supply chain components
- Regulatory system poorly suited to evaluate and license
  small power reactors
  - Regulatory environment not adapted for SMRs and micro-reactors
  - Balkanized structure of regulatory oversight, with authority distributed among NRC, Department of Energy, and Department of Defense
- Questionable financial viability of broader market for new technology

NuScale Lesson

- SMR/MMR systems embedded within institutional, legal, and infrastructural world nurtured on large reactor systems
- High and unpredictable startup costs for first-of-a-kind (FOAK) reactor
  - SMR/MMR economics collapse when FOAK facility encounters realities of nuclear construction (i.e., non-linear cost reduction compared to large reactor facilities)
  - NuScale SMR project with Utah Associated Municipal Power Systems terminated when levelized cost ballooned to >$20,000 per kilowatt

Offshore Floating Nuclear Power Plant

Offshore Floating Nuclear Power Plant

Characteristics include:

- Reduced construction cost
  - Completely built in existing shipyard
  - No excavation work, structural concrete, or temporary facilities
- Enhanced quality
- Easier to scale and deploy
- More siting flexibility
- More affordable
- Safer
  - No earthquake or tsunami concerns
  - Ocean heat sink ensures infinite passive decay heat removal

Akademik Lomonosov at Pevek

Nuclear Fusion

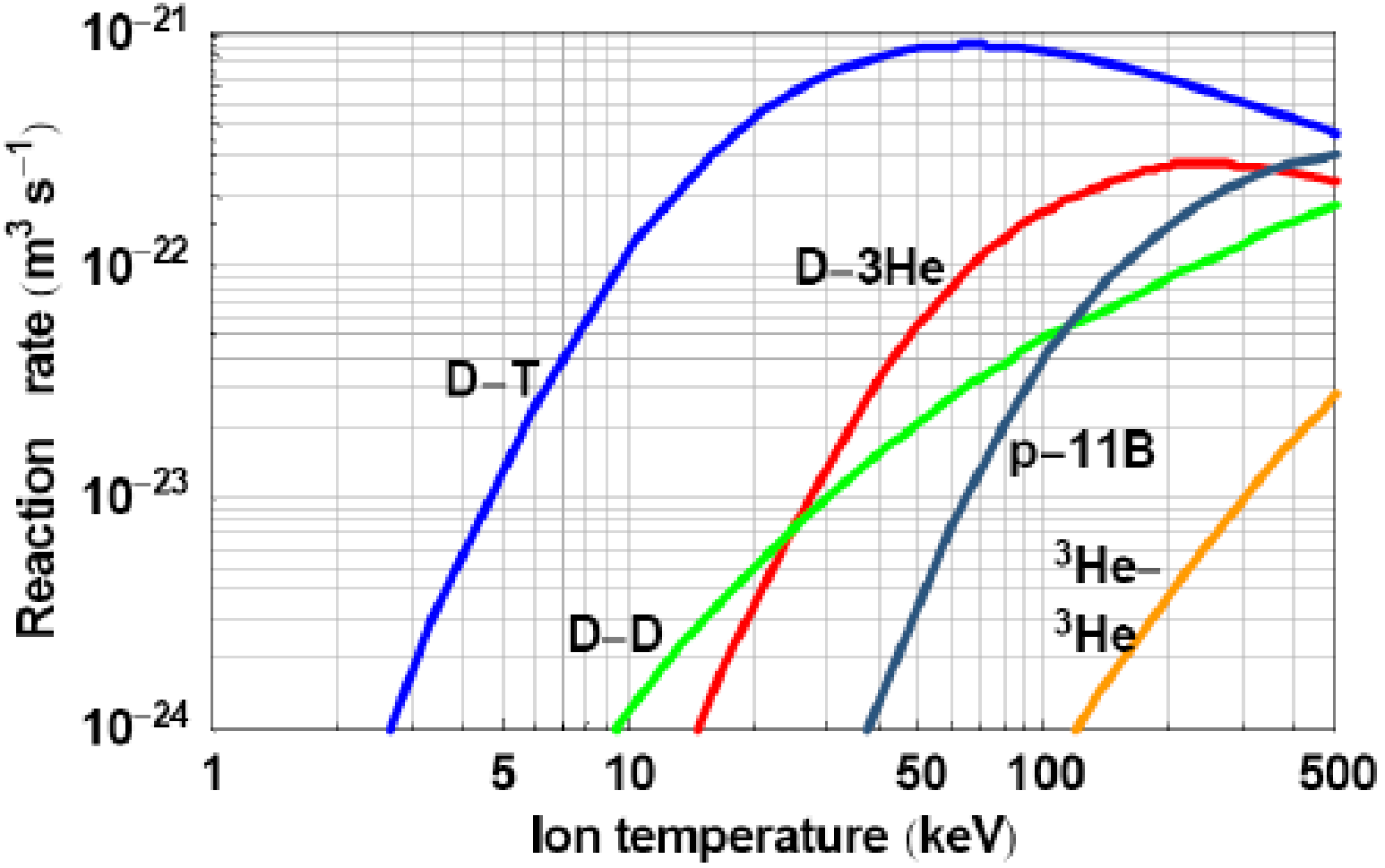
What is Fusion Energy?

- Fusion reactions power sun and stars
- In terrestrial fusion, plasma of ionized gas formed from hydrogen isotopes (deuterium and tritium) under high temperature (100 million degrees Celsius) and pressure to produce high energy neutrons and helium nuclei

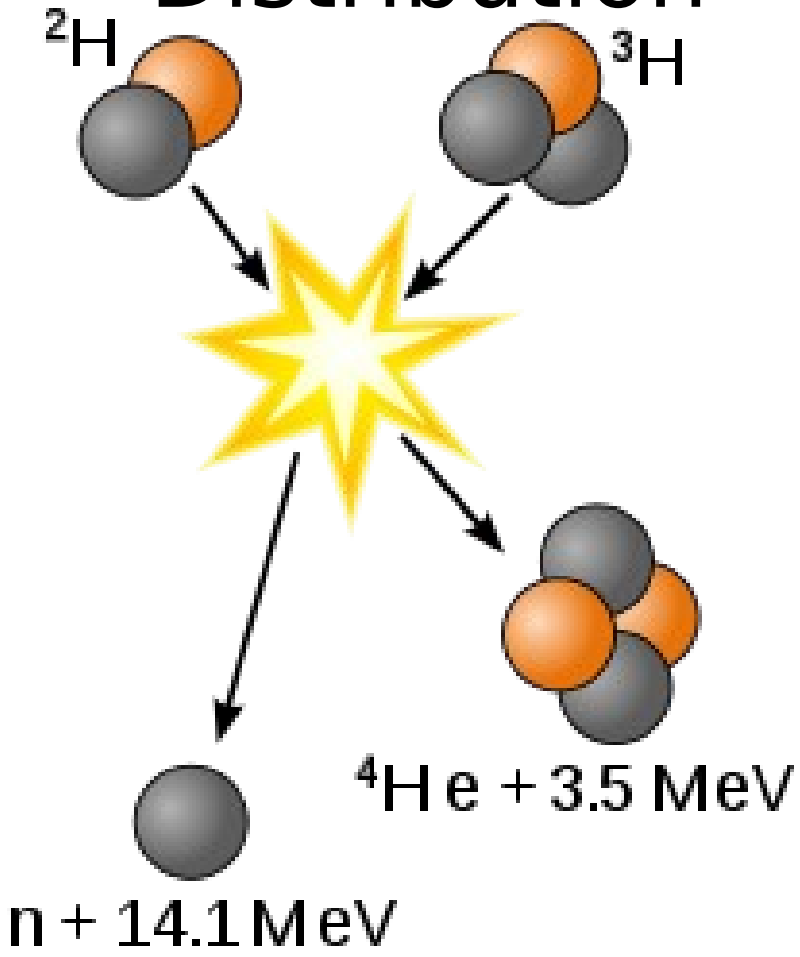
Potentially Useful Fusion Reactions

Reaction	Shorthand notation	Reaction energy (MeV)	Threshold plasma temperature (keV)	Maximum energy gain per fusion
${}_1^2\mathrm{D} + {}_1^3\mathrm{T} \rightarrow {}_2^4\mathrm{He} + {}_0^1\mathrm{n}$	D-T	17.6	10	1800
${}_1^2\mathrm{D} + {}_1^2\mathrm{D} \rightarrow {}_2^3\mathrm{He} + {}_0^1\mathrm{n}$	D-D	3.2	50	70
${}_1^2\mathrm{D} + {}_1^2\mathrm{D} \rightarrow {}_1^3\mathrm{T} + {}_1^1p$	D-D	4.0	50	80
${}_1^2\mathrm{D} + {}_2^3\mathrm{He} \rightarrow {}_2^4\mathrm{He} + {}_1^1p$	D-^{3}He	18.3	100	180
${}_5^{11}\mathrm{B} + {}_1^1p \rightarrow 3{}_2^4\mathrm{He}$	p-^{11}B	8.7	300	30

Fusion Reaction Rate vs Plasma Temperature



D-T Fusion Particle Energy Distribution



D-T Fusion Energy Disposition

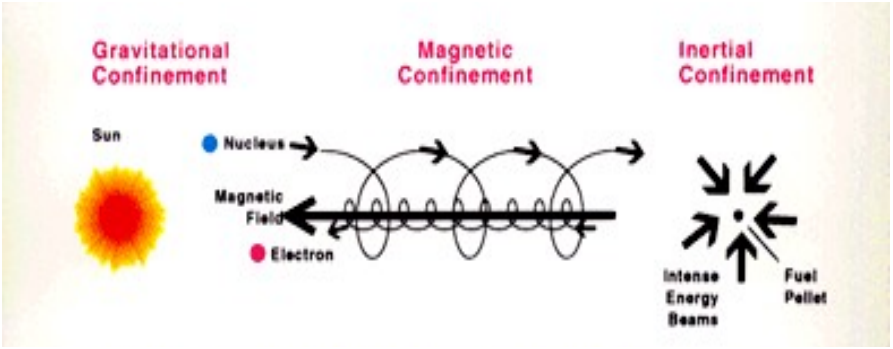
	MeV	%
He-4 Kinetic Energy	3.5	20
Neutron Kinetic Energy	14.1	80
Total	17.6	100

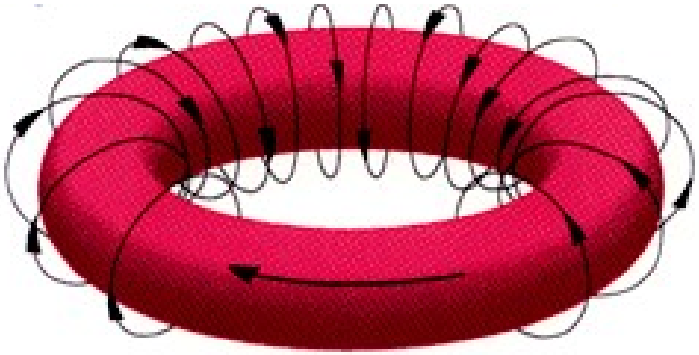
Ideally, He-4 nuclei (alpha particles) will expend energy in plasma providing additional heating

Energy of 14.1 MeV neutrons would be captured in lithium blanket that produces more tritium and heat

Lithium blanket would be cooled by system's primary coolant, which can transfer heat via heat exchanger to working fluid of conventional power cycle to generate electricity

Plasma Confinement

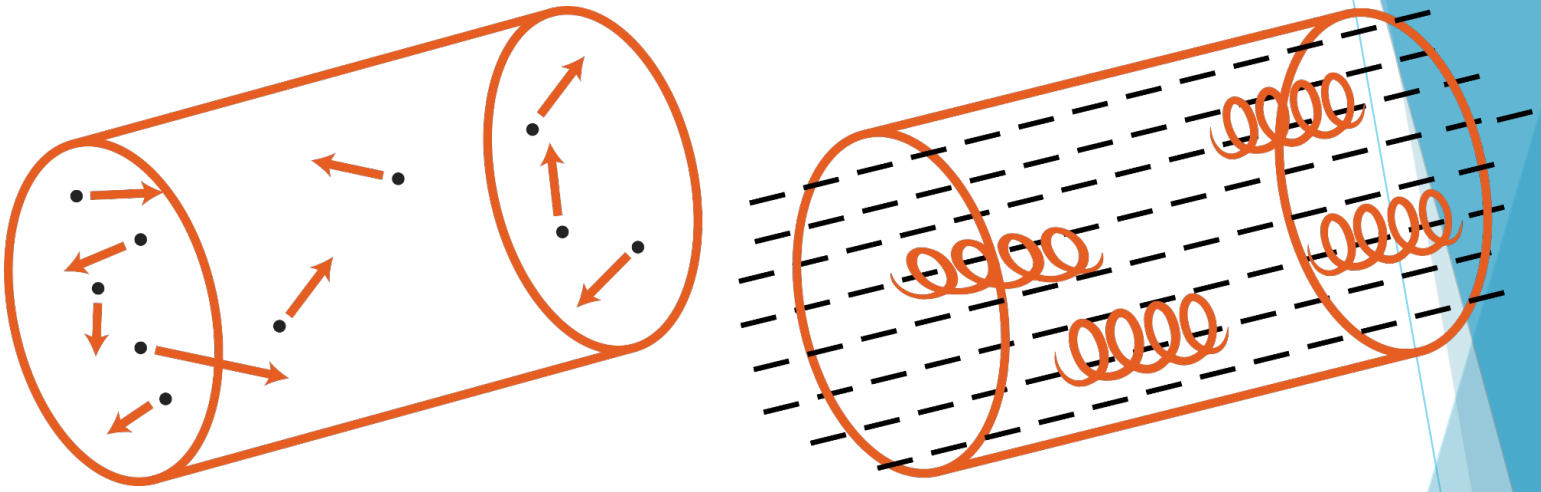




Most common magnetic confinement scheme is Tokamak

- Gravitational confinement (stars)
- Magnetic confinement (plasma confined by magnetic fields – many configurations)
- Inertial confinement (inward energy-directed momentum confines plasma long enough for reactions to take place)

Principle of Magnetic Confinement



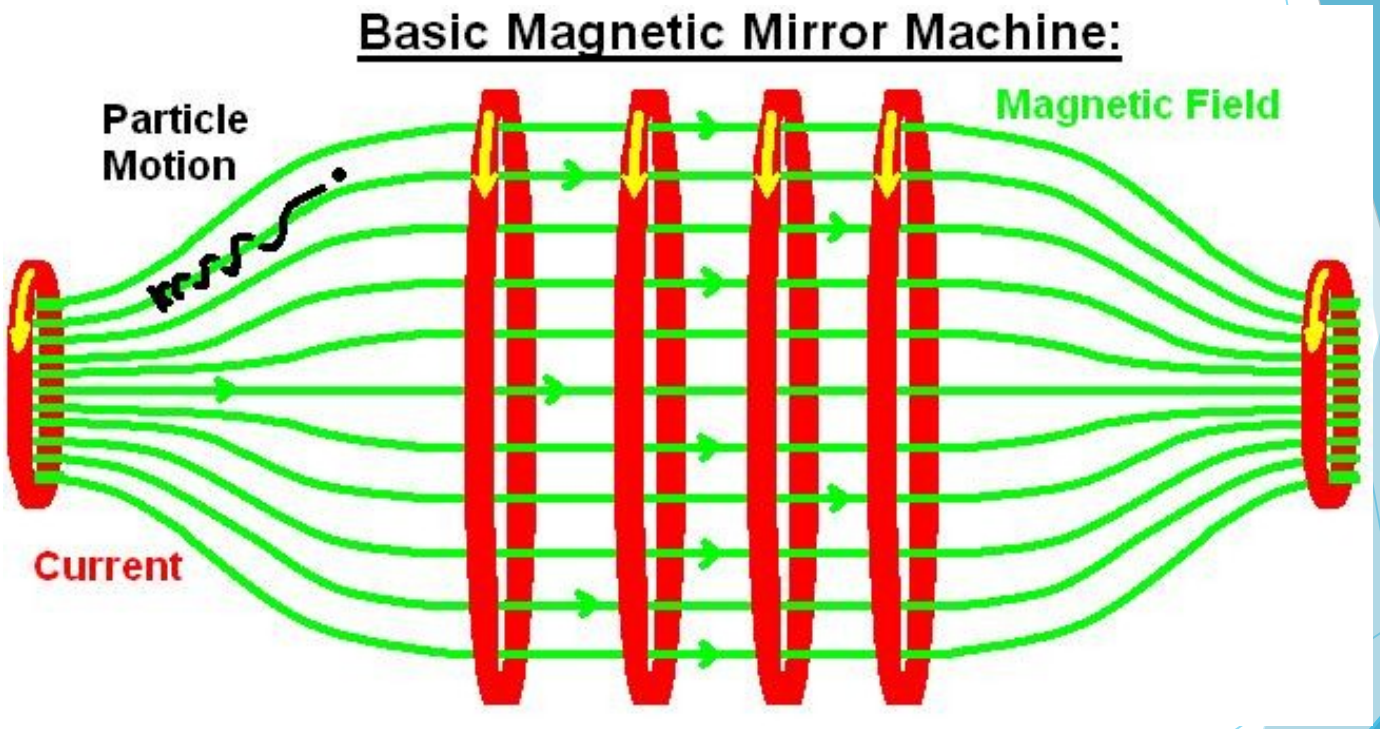
Charged particles (ions and electrons) captured by magnetic field lines parallel to axis of confinement volume

Electrons and positively charged ions travel in opposite directions around magnetic field lines

Magnetic Confinement Fusion

- Magnetic mirror machines
  - One of earliest approaches to fusion power along with stellarator and Z-pinch machines
  - Little development since 1970s
- Z-pinch
  - Two U.S. companies pursuing magneto-inertial Z-pinch fusion reactors
- Toroidal machines
  - Tokamaks and stellarators two leading magnetic confinement fusion candidates

Magnetic Confinement Machines

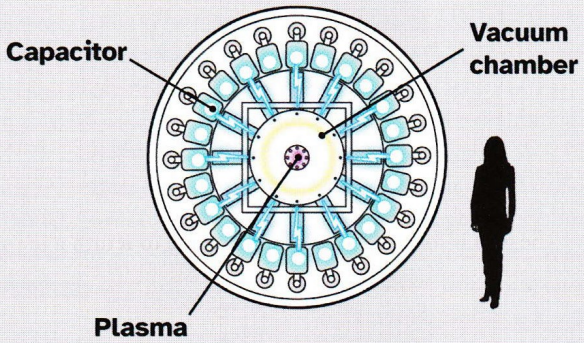


Z-Pinch Fusion

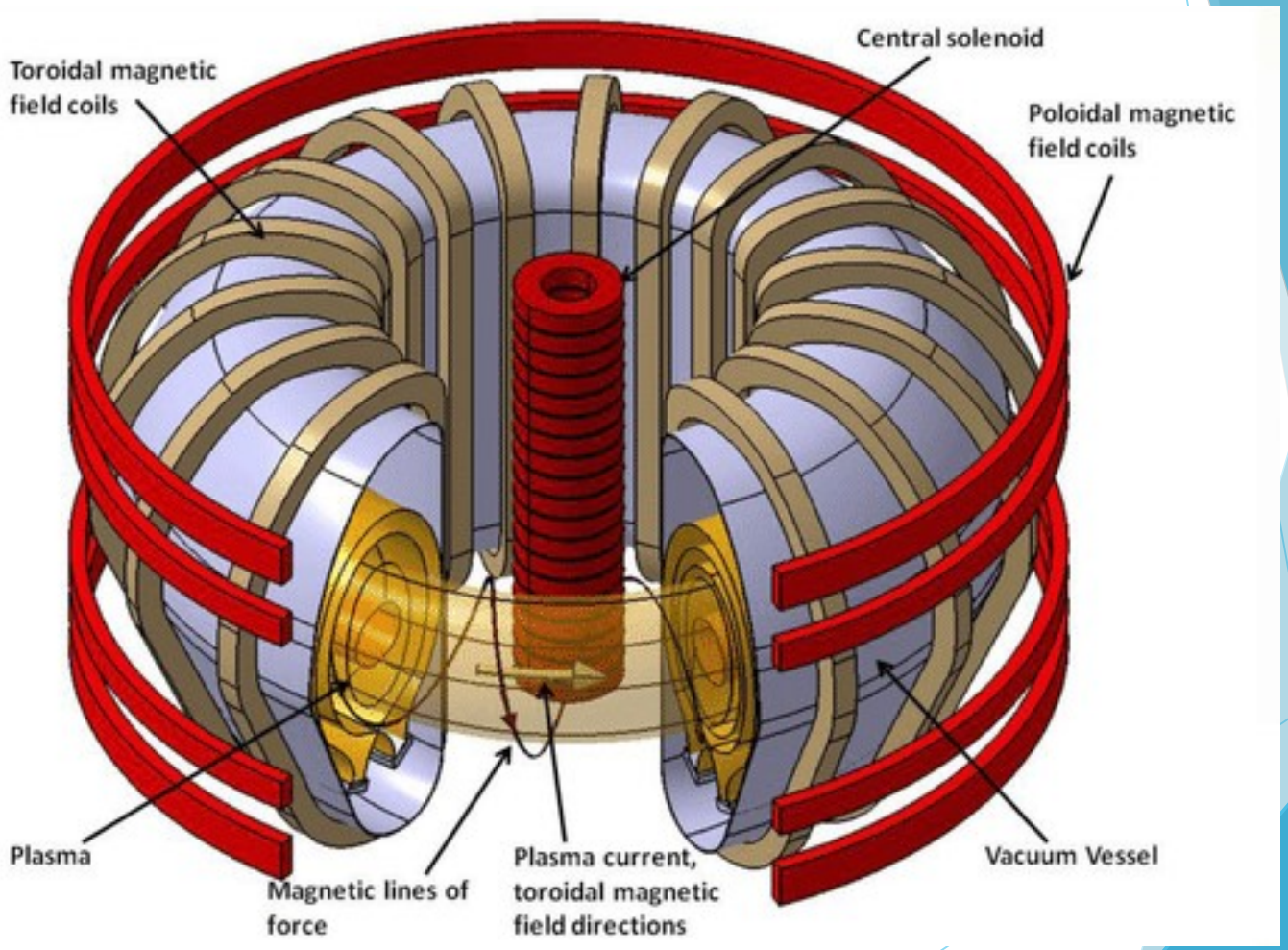
Z-PINCH

Instead of using external magnets to confine a plasma, reactors like the PPML's MAIZE machine use the Z-pinch principle. An ultra-powerful electrical field is applied to the plasma, causing it to generate a magnetic field that squeezes it into a fine line.

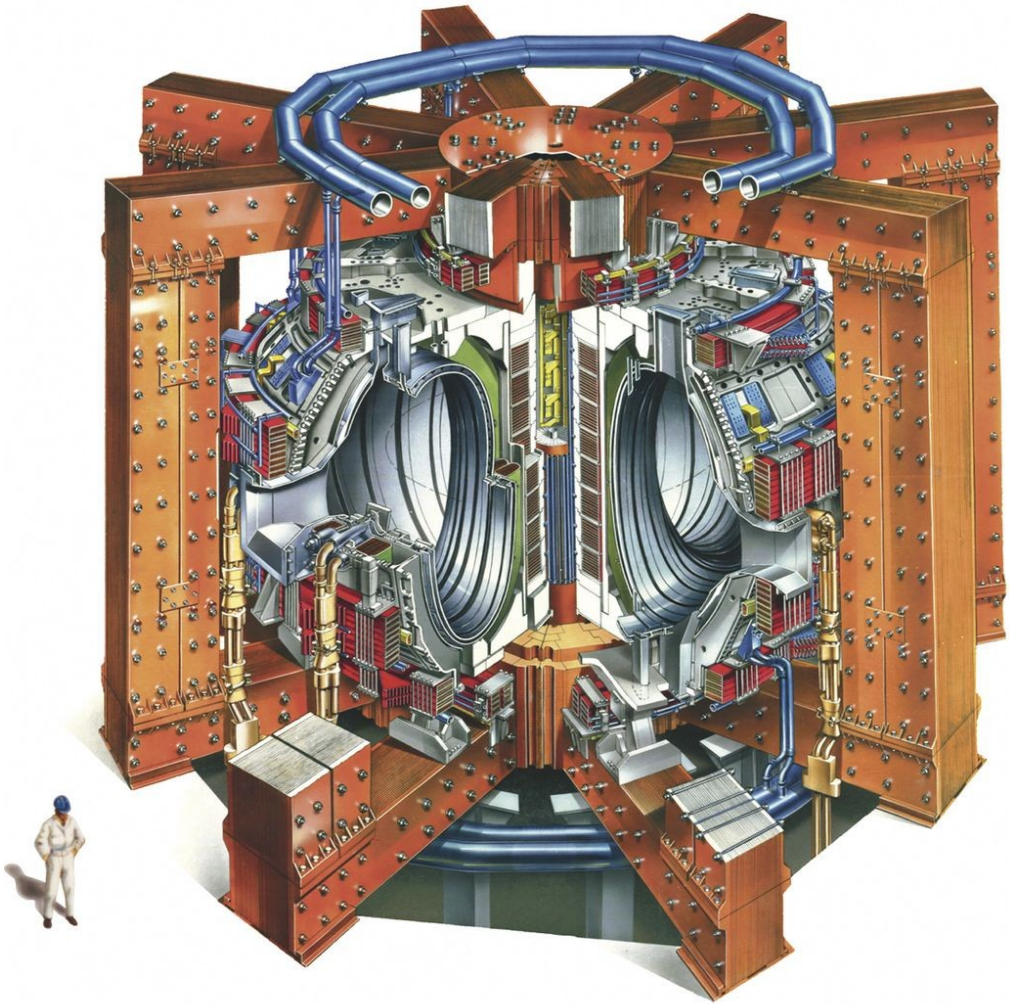
The MAIZE machine uses 80 high-voltage capacitors and 40 switches arranged in a 9.8-foot diameter circle around a vacuum chamber. The capacitors discharge their energy through a small column of deuterium gas in the center of the vacuum chamber, compressing it on the z-axis (a "Z-pinch") and progressing toward plasma densities and temperatures that could one day induce a fusion reaction.



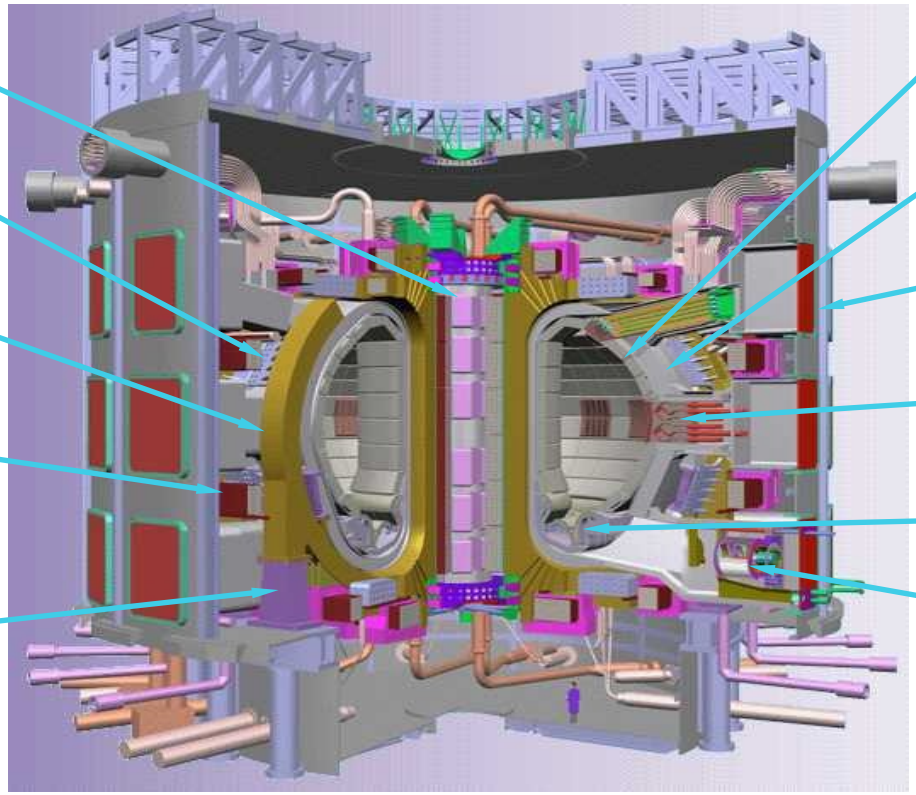
Magnetic Fields in a Tokamak



Joint European Torus (JET) Reactor

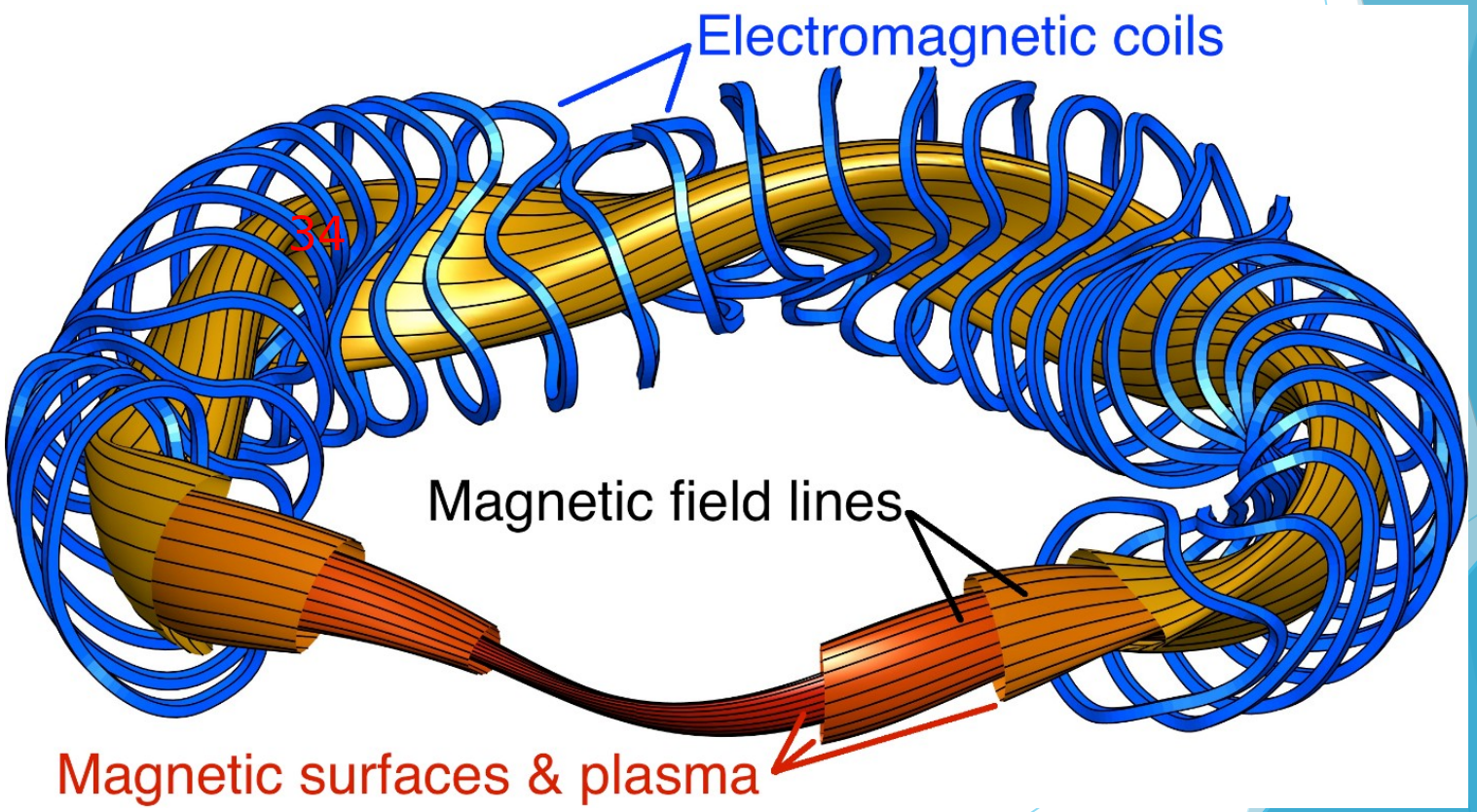


International Thermonuclear Experimental Reactor (ITER)

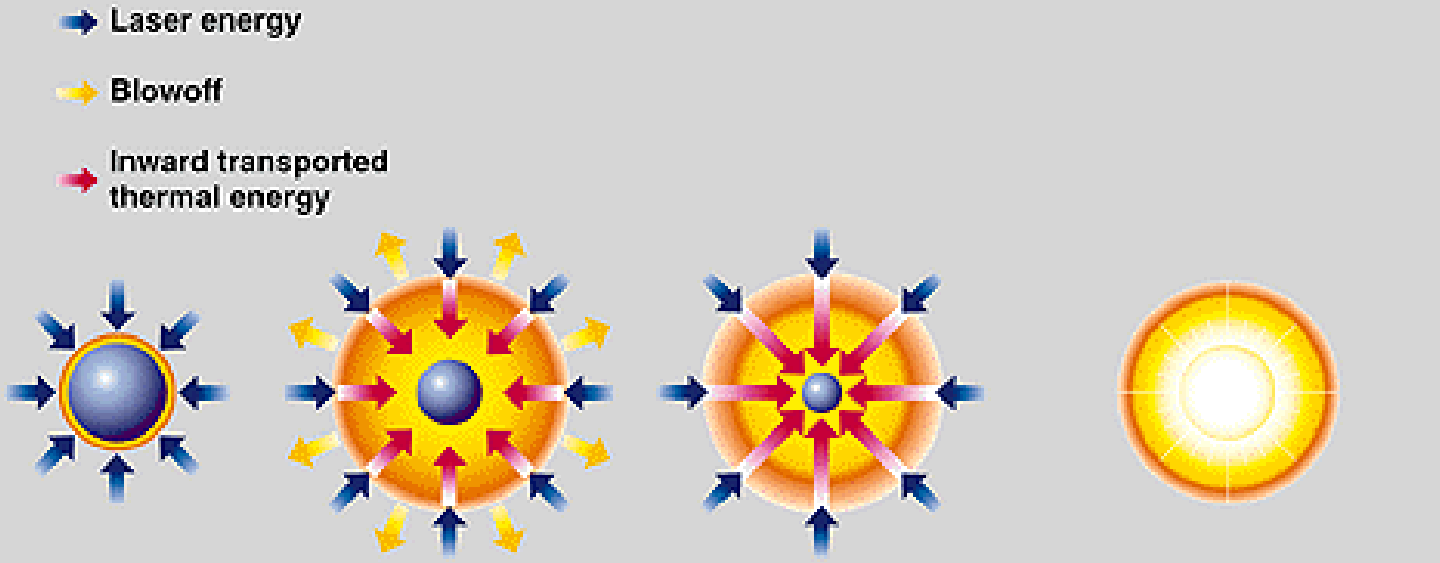


Magnetic Confinement Machines (CONT.)

STELLARATOR



The Inertial Confinement Fusion Concept



Laser beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Fuel is compressed by the rocket-like blowoff of the hot surface material.

During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.

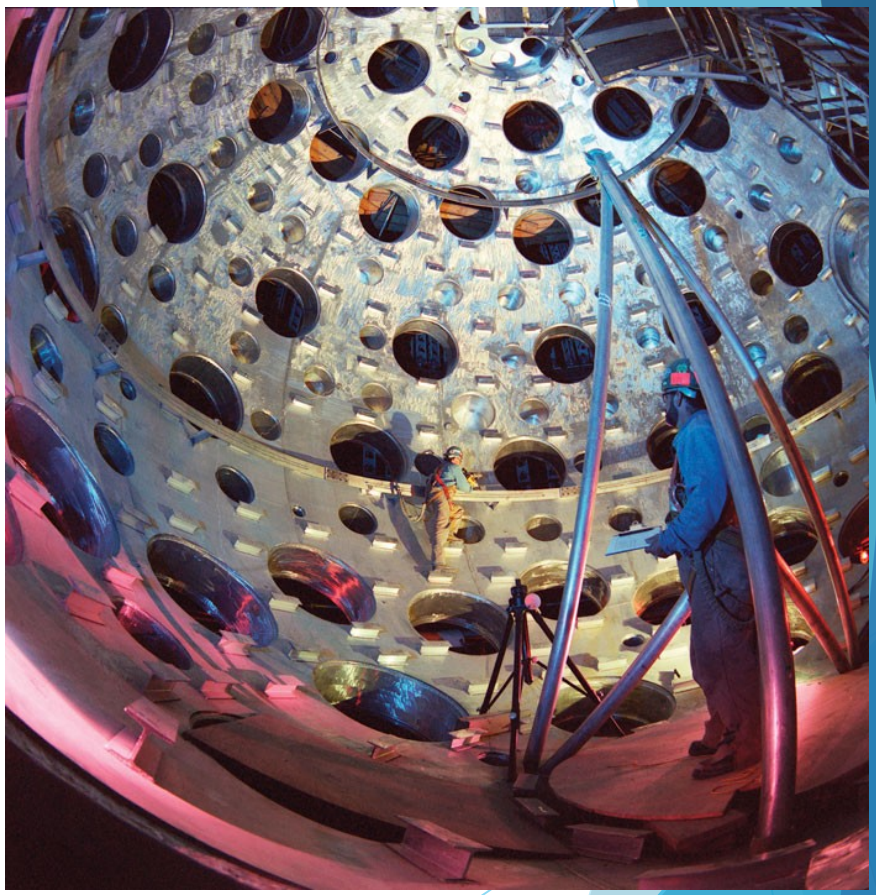
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

Principle of Inertial Confinement

- Induce a shock wave in target
- D-T fuel is compressed to high temperature and density
- Fusion begins and continues until required density and temperature of DT fuel can no longer be sustained (< 20 nanoseconds)
- Target: D-T ice (Temp = 18^{o} Kelvin or -255^{o} Celsius)

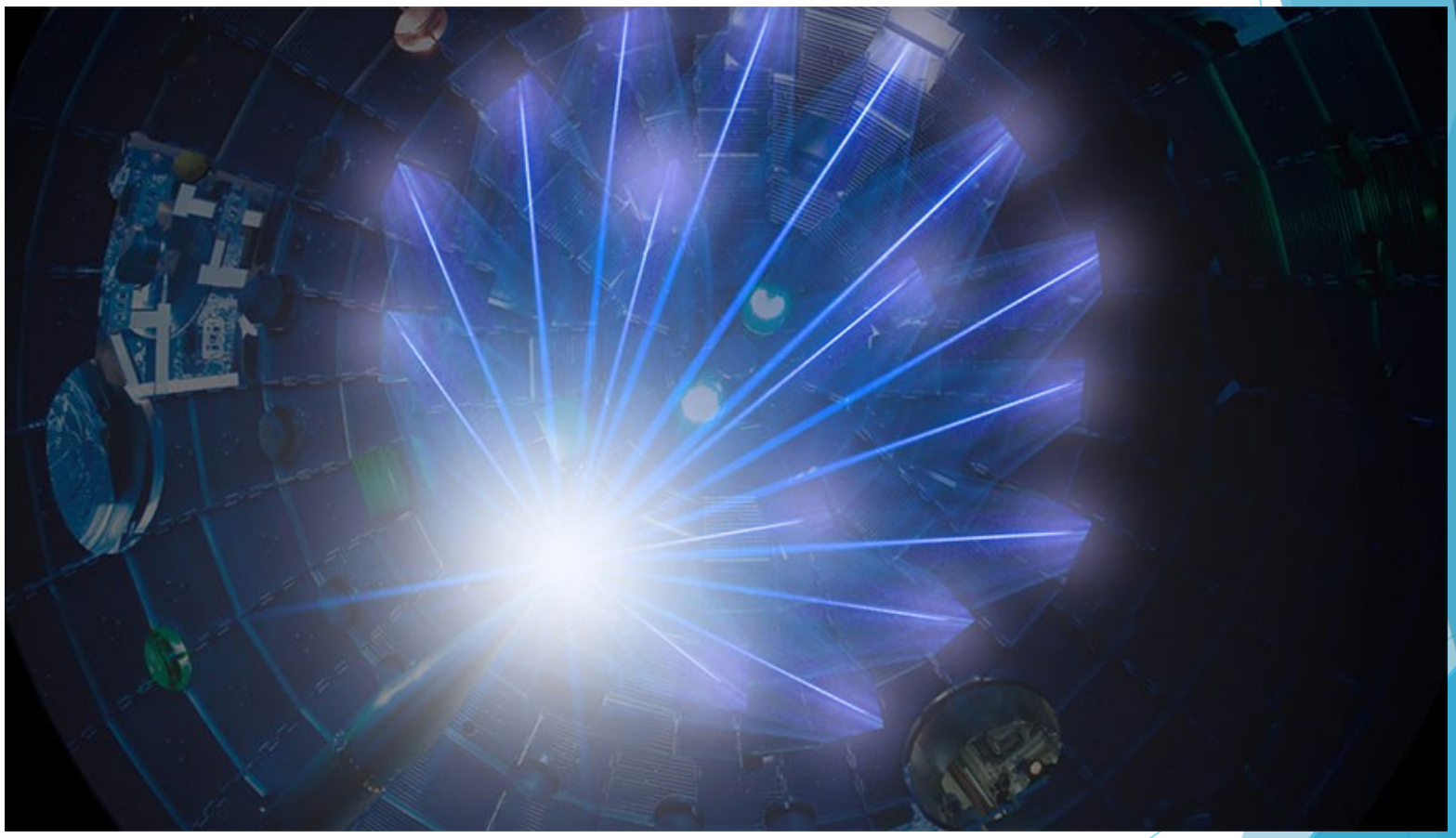
Laser-Driven Inertial Confinement

- 192 lasers aimed in perfect symmetry onto target
- Laser “boils” off outer layer of target
- Force of boiling sends shock wave through target causing fusion

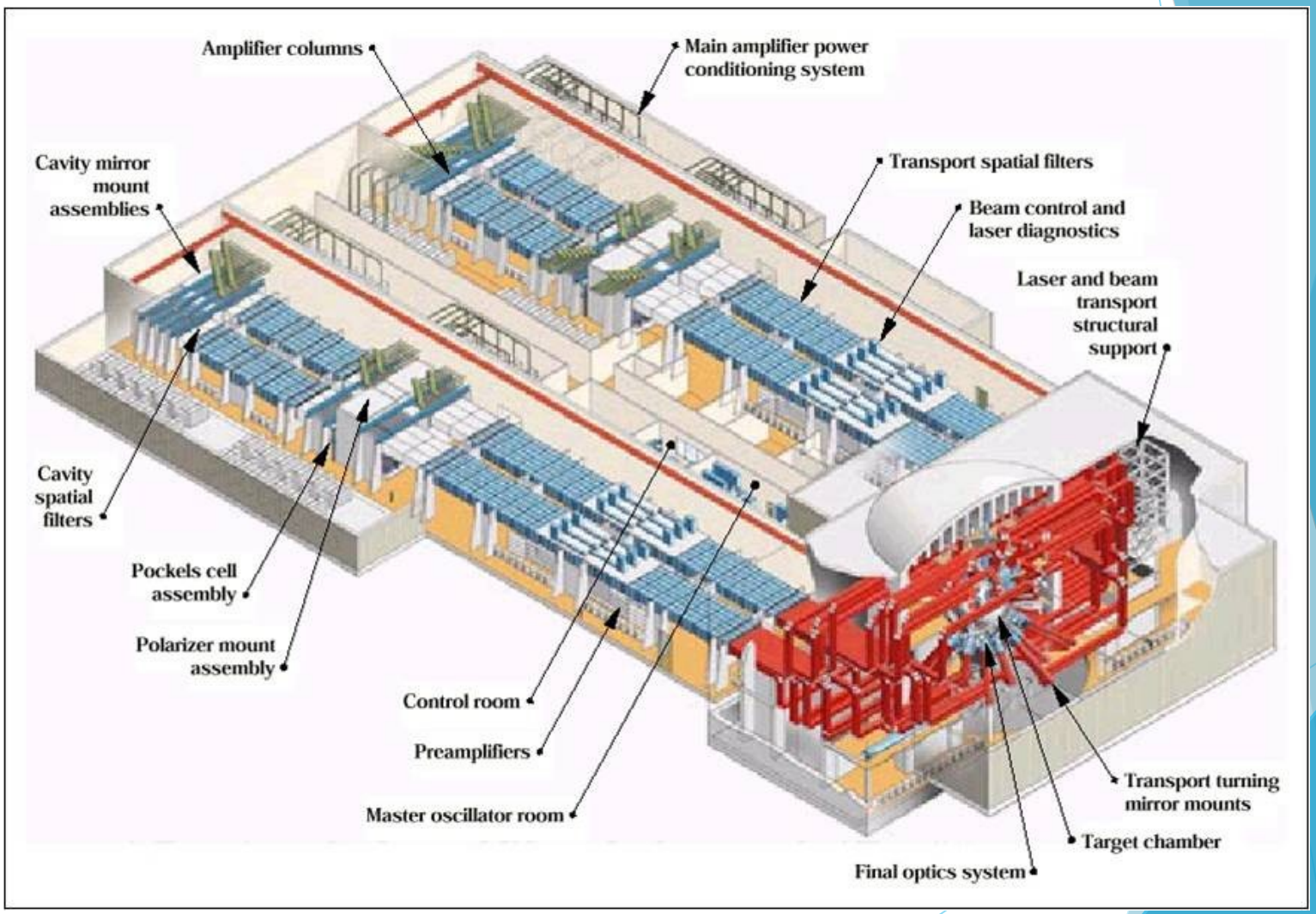


National Ignition Facility target chamber

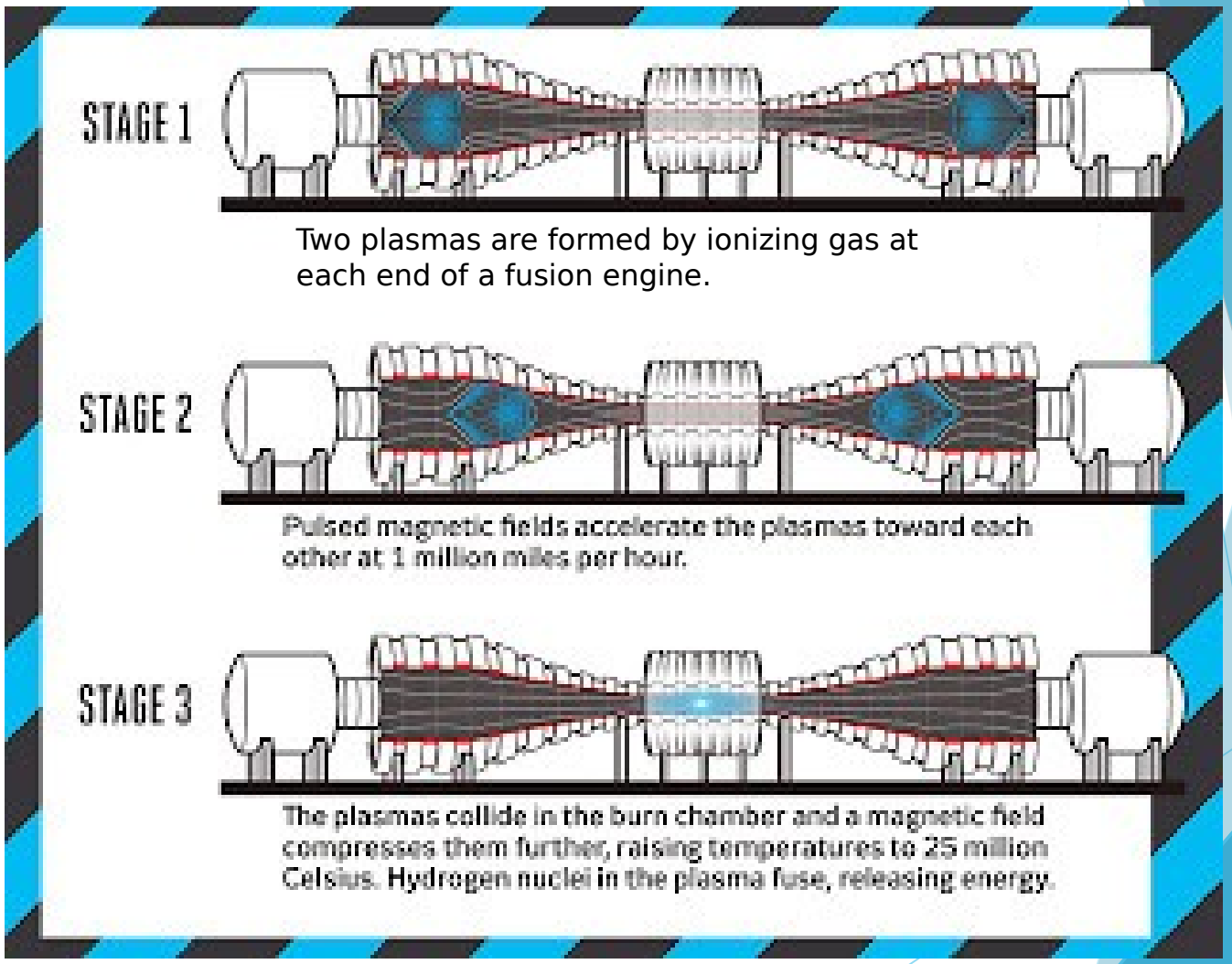
Laser-Driven Inertial Confinement (cont.)



National Ignition Facility (NIF)



Colliding Beam Fusion


STAGE 1
Two plasmas are formed by ionizing gas at each end of a fusion engine.
STAGE 2
Pulsed magnetic fields accelerate the plasmas toward each other at 1 million miles per hour.
STAGE 3
The plasmas collide in the burn chamber and a magnetic field compresses them further, raising temperatures to 25 million Celsius. Hydrogen nuclei in the plasma fuse, releasing energy.

Assessing Fusion Energy Success

Fusion energy gain factor, Q, is ratio of fusion power produced to power required to maintain plasma in steady state

- Scientific breakeven (Q = 1)
  - Power released equals required heating power
- Engineering breakeven (Q = 5-8 for magnetic confinement, 50-100 for inertial confinement)
  - More power out of plant than in
- Commercial breakeven
  - Economic value of sold electricity sufficient to pay for plant (may not be achievable)

Fusion Energy Necessary for Engineering Breakeven

Net fusion reaction energy must be sufficient to

- Maintain pressure, temperature, and density conditions for sustained fusion reaction
- Inject fusion reactants into machine
- Remove reaction-quenching matter from fusion reaction
- Power all fusion plant auxiliary systems, including
  - tritium scavenging and reinjection systems
  - lithium blanket heat removal system
  - cryogenic system
  - energy conversion system components necessary to obtain useful electricity

The Realities of Fusion

- Economic realities
  - High operating costs
    - Skilled personnel required to operate fusion reactor's more complex subsystems including cryogenics, tritium processing, plasma heating equipment, and elaborate diagnostics – may require double number of employees for fission reactor operation
  - Large coolant demands to transfer heat to energy conversion devices
  - Huge parasitic power consumption
    - Power needed to control plasma in magnetic confinement systems and to ignite fuel capsules in pulsed inertial confinement systems
    - Power for auxiliary systems essential to operation (e.g., cryogenic system)

The Realities of Fusion (cont.)

- Energetic neutron streams lead to
  - Radiation damage to fusion machine structures
    - Swelling, embrittlement, and fatigue expected to be worse than in fission reactor pressure vessels
  - Radioactive waste from neutron activation of structural and non-structural component materials
    - While radioactivity level per kg of waste much smaller, volume and mass of waste much larger than fission reactor waste
  - Need for biological shielding
    - Maintenance activities require remote handling and robot use
  - Potential for production of weapons-grade Pu-239
    - Must comply with IAEA safeguards to prevent Pu production or tritium diversion

The Realities of Fusion (cont.)

- Tokamak plasma instabilities called Edge Localized Modes (akin to solar flares)
  - Can vaporize areas of Tokamak wall if not suppressed
  - Can trigger larger instabilities that rapidly dump entire plasma energy creating huge electromagnetic forces that can catastrophically destroy Tokamak walls
- Many physics and technology features essential for fusion power plants require substantial development and testing in fusion environment (e.g., wall protection systems already approaching physical limits)

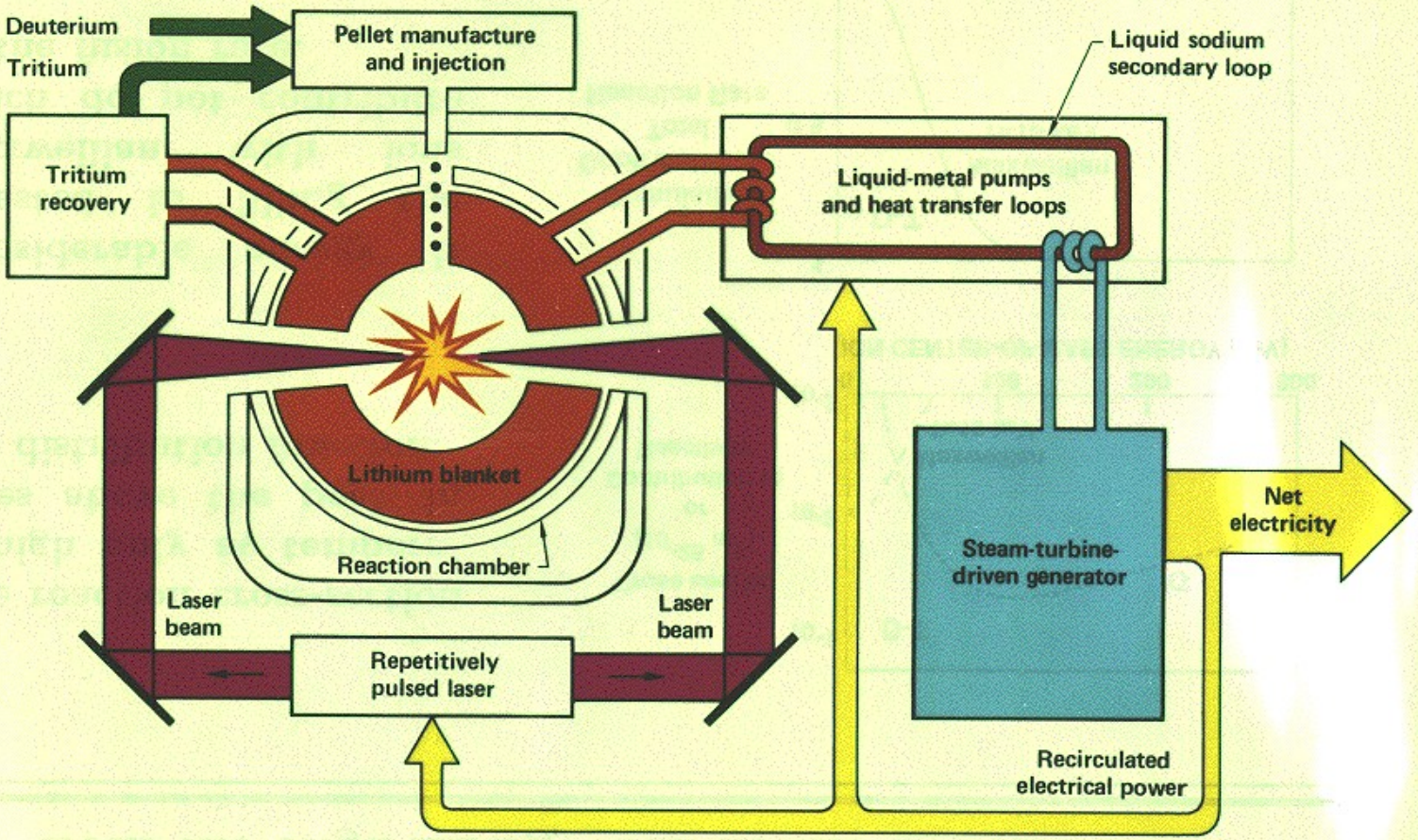
The Realities of Fusion (cont.)

- Tritium fuel issues
  - No proven solutions for fusion fuel cycle, which involves breeding and reprocessing unprecedented quantities of tritium
  - Approximately equal mixture of deuterium and tritium may be only feasible fuel for foreseeable future, which necessitates lithium “breeding” in fusion reactor; to date no large-scale lithium breeding system attempted, and unknown whether such system possible to create
  - Less than 10% of injected tritium burned in magnetic confinement device before escaping reacting region; scavenging from surfaces and interiors of fusion reactor subsystems and re-injection 10 to 20 more times required for complete burning

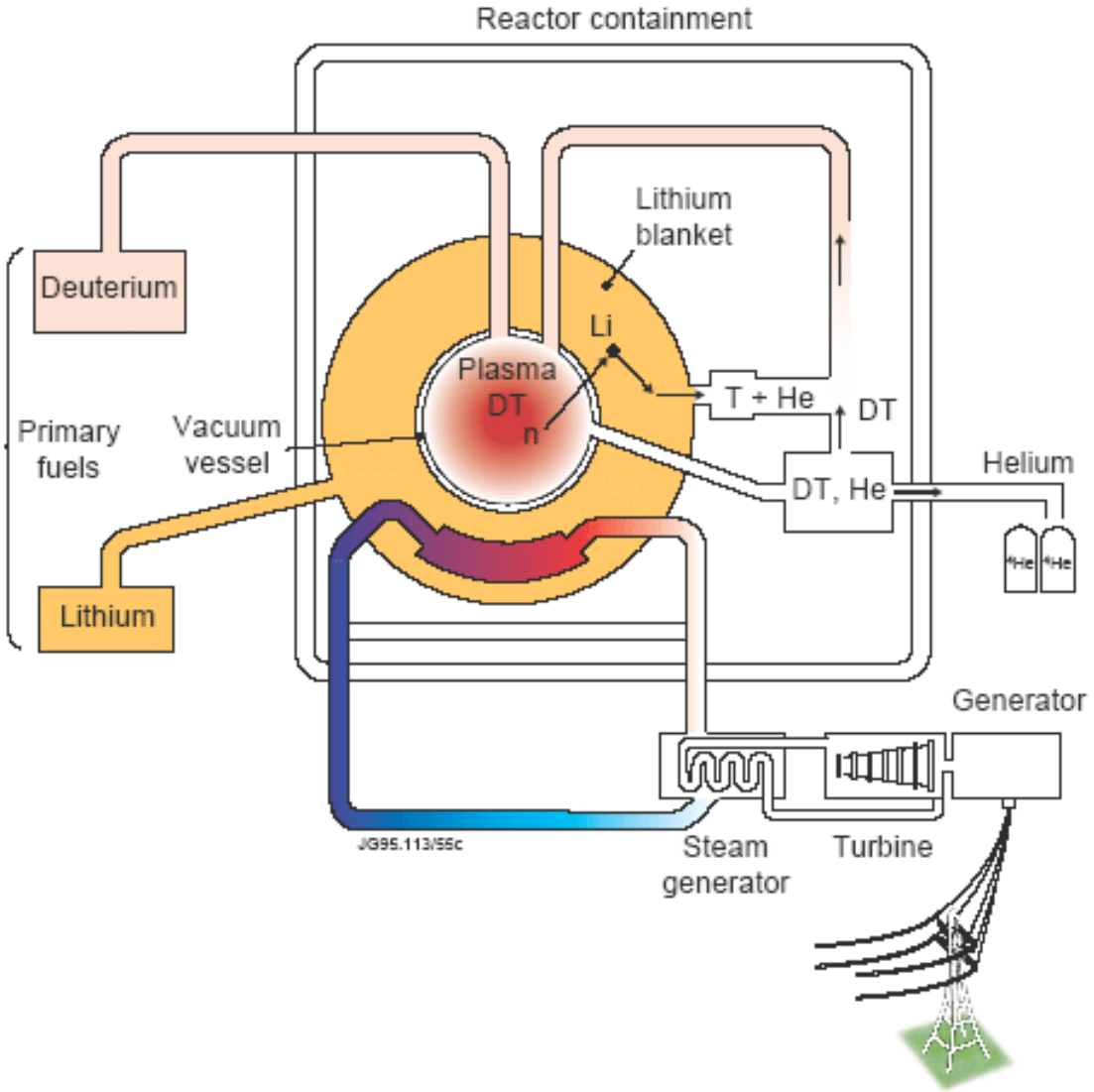
The Realities of Fusion (cont.)

- Tritium fuel issues (cont.)
  - Tritium burnup in inertial confinement device not significantly better
  - 10% of injected tritium may not be recoverable; shortfall may necessitate external supply from fission reactors
  - Enormous expense of tritium production in fission reactors may mean only fusion reactors fueled solely with deuterium will be practical

A FUNCTIONAL DIAGRAM OF A LASER FUSION POWER PLANT

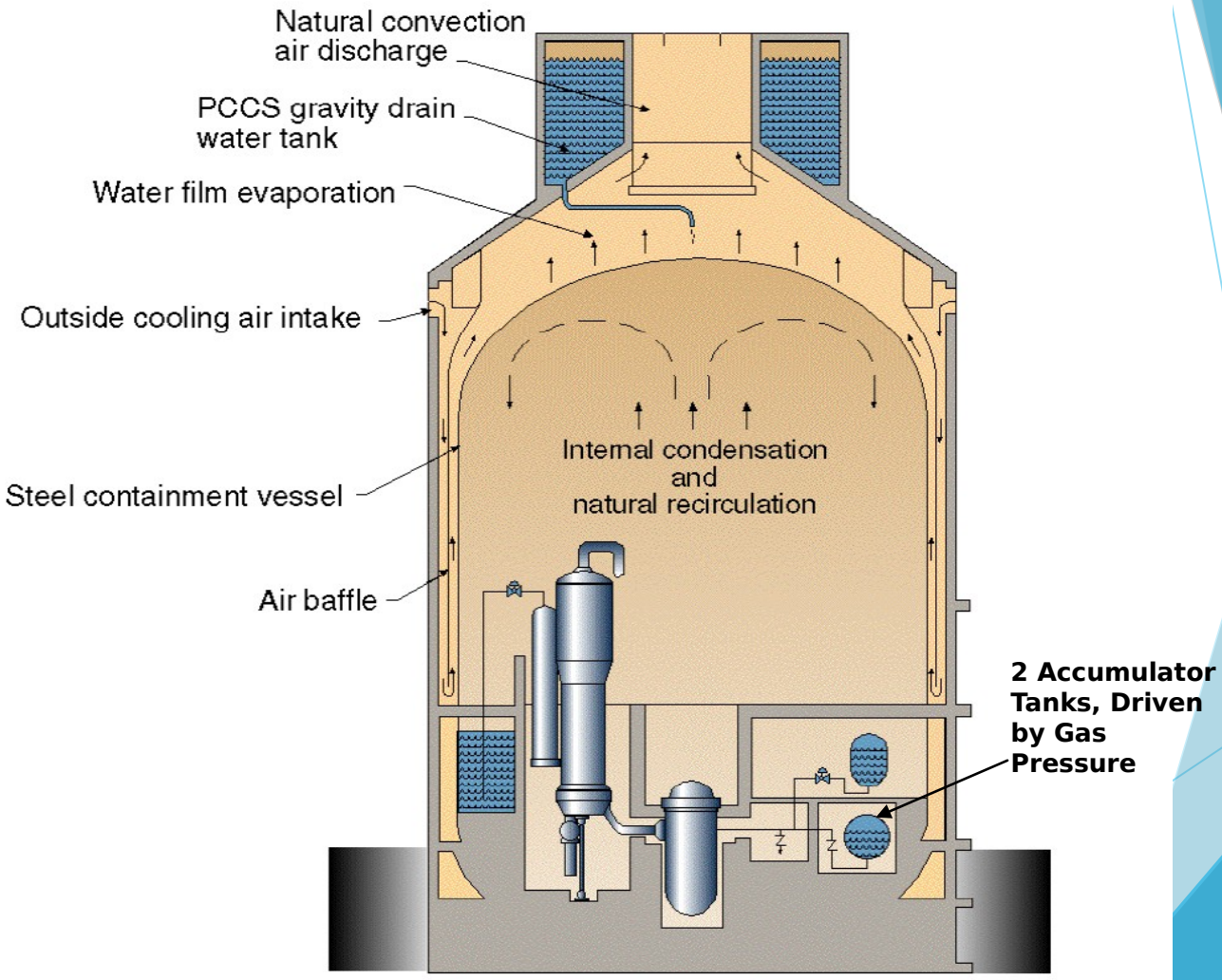


Functional Diagram of Tokamak Fusion Power Plant

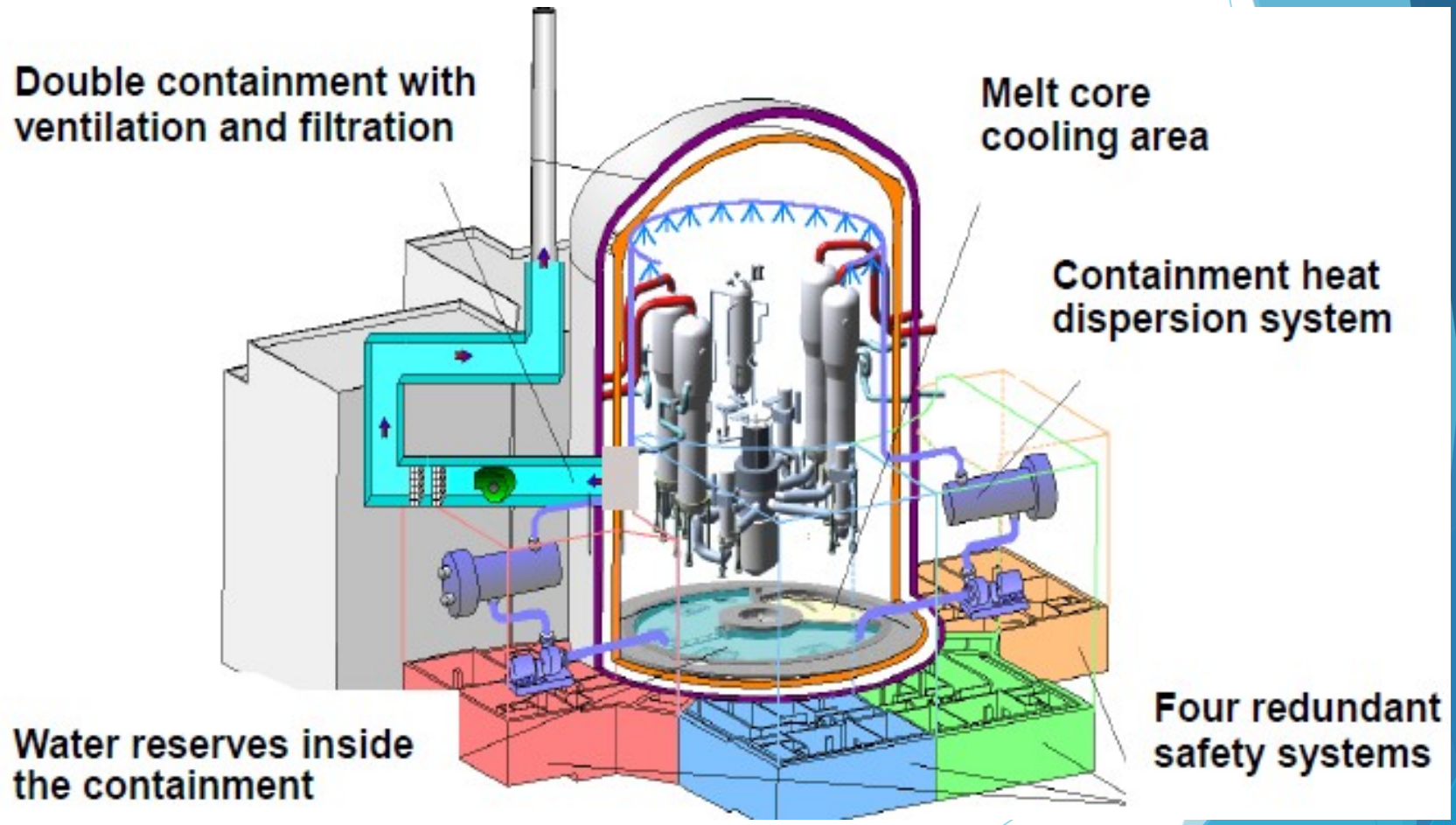


Supplemental Slides

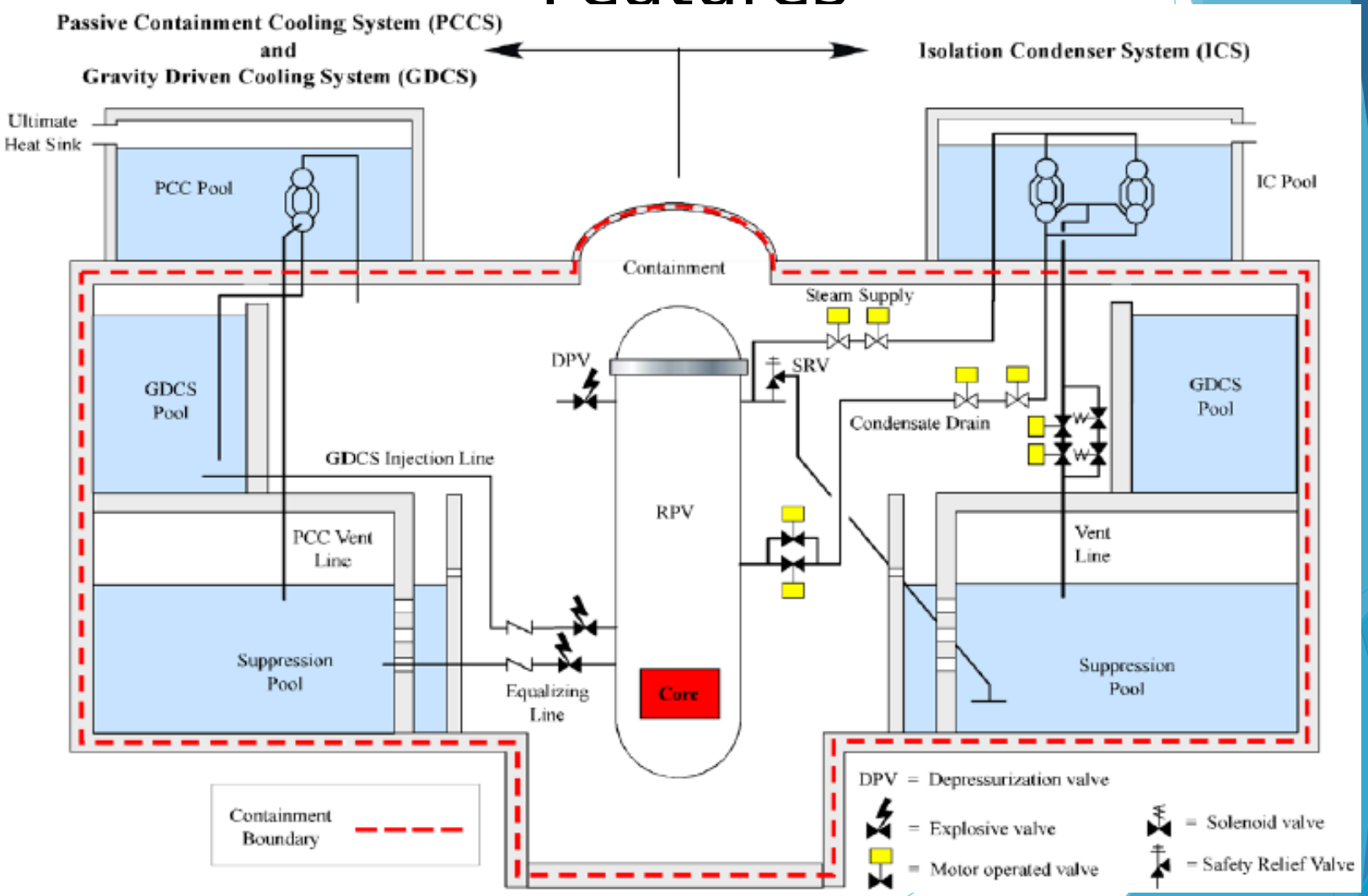
AP-1000 Passive Heat Removal Systems


Natural convection air discharge
PCCS gravity drain water tank
Water film evaporation
Outside cooling air intake
Steel containment vessel
Air baffle
Internal condensation and natural recirculation
2 Accumulator Tanks, Driven by Gas Pressure

Evolutionary Power Reactor (EPR) Safety Features

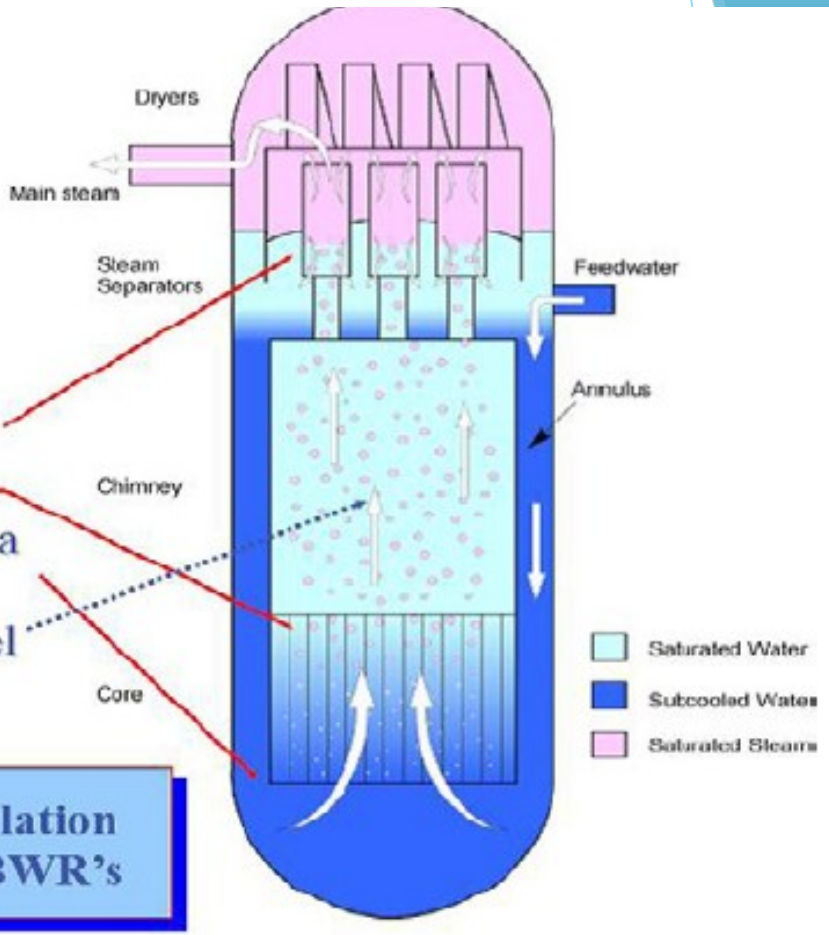

Double containment with ventilation and filtration
Melt core cooling area
Containment heat dispersion system
Water reserves inside the containment
Four redundant safety systems

Economic Simplified BWR Safety Features



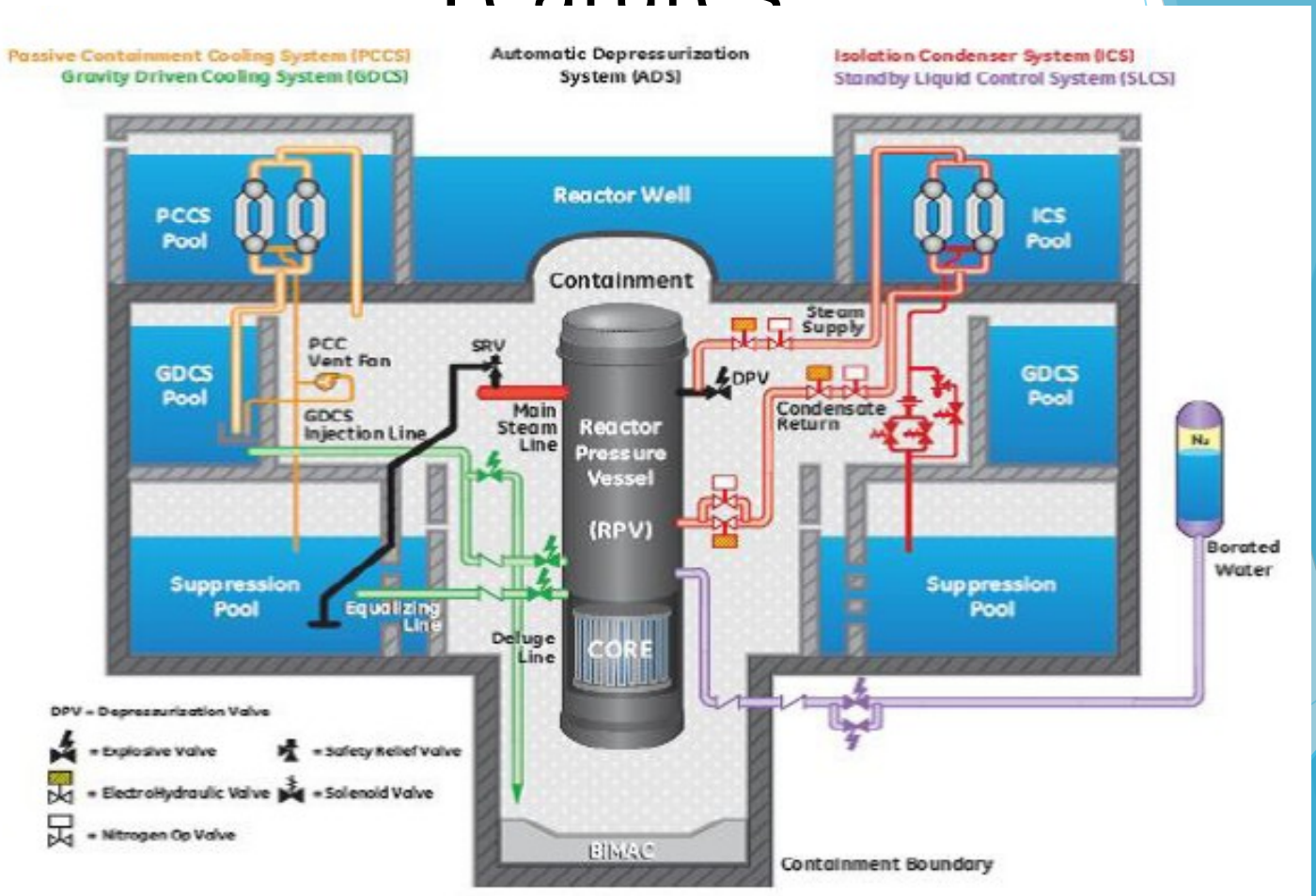
Economic Simplified BWR Safety Features

- Reduced flow restrictions
  - improved separators
  - shorter core
  - increase downcomer area
- Higher driving head
  - chimney and taller vessel



Enhanced Natural Circulation Compared to Standard BWR's

Economic Simplified BWR Safety Features



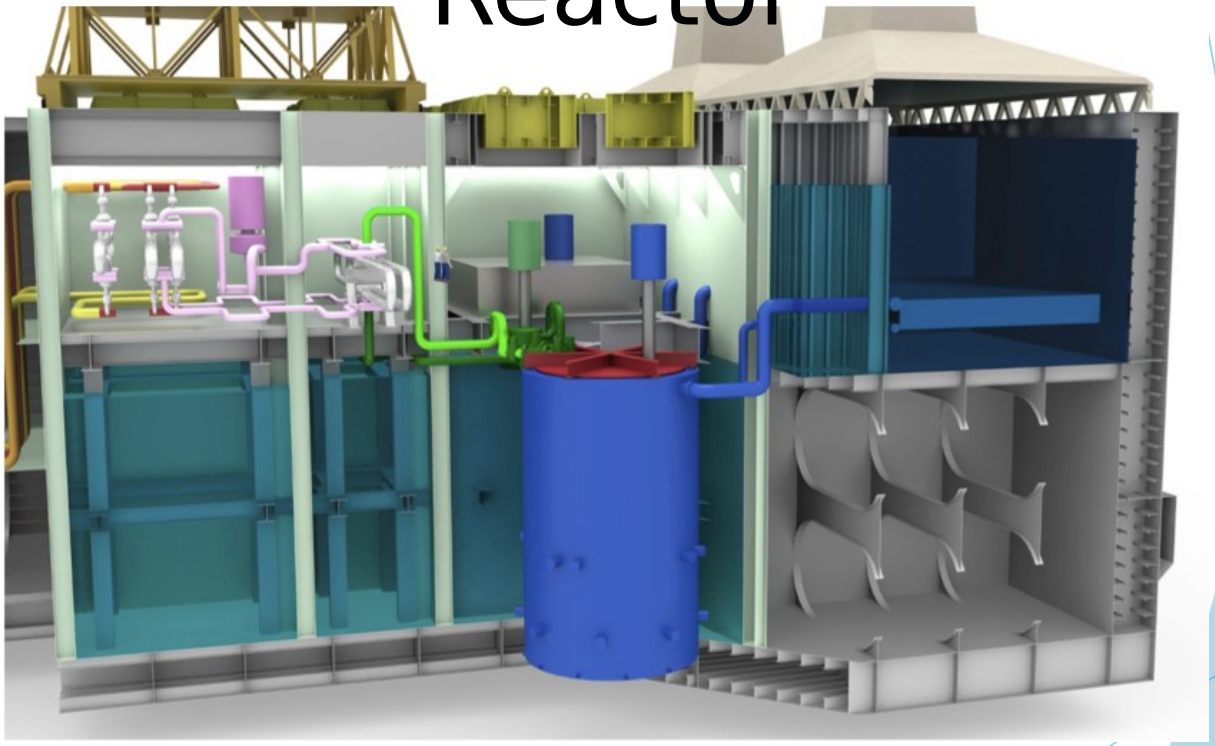
Generation III Light-Water Reactors

Name	Power Level (MWe)	Coolant	Safety Risk	Fuel Cycle/ Waste	Economics	Experience Base; Licensing	Nonproliferation
AP-1000	1,115 PWR	water	Low	medium	medium	limited; licensed	medium
ESBWR	1,600 BWR	water	low	medium	medium	limited; licensed	medium
APR-1400	1,450 PWR	water	medium	medium	medium	limited; licensed	medium
EPR PWR	1,660 PWR	water	medium	medium	medium	limited; licensed	medium
VVER-1200	1,198 PWR	water	medium	medium	medium	limited; licensed	medium
ABWR	1,371 BWR	water	medium	medium	medium	operating	medium
APWR	1,530 PWR	water	medium	medium	medium	limited; licensed	medium
CPR-1000	1,030 PWR	water	medium	medium	medium	operating	medium
ACPR-1000	1,150 PWR	water	low	medium	medium	limited; licensed	medium
HPR-1000	1,150 PWR	water	medium	medium	medium	limited; licensed	medium
CAP-1400	1,500 PWR	water	medium	medium	medium	limited; licensed	medium

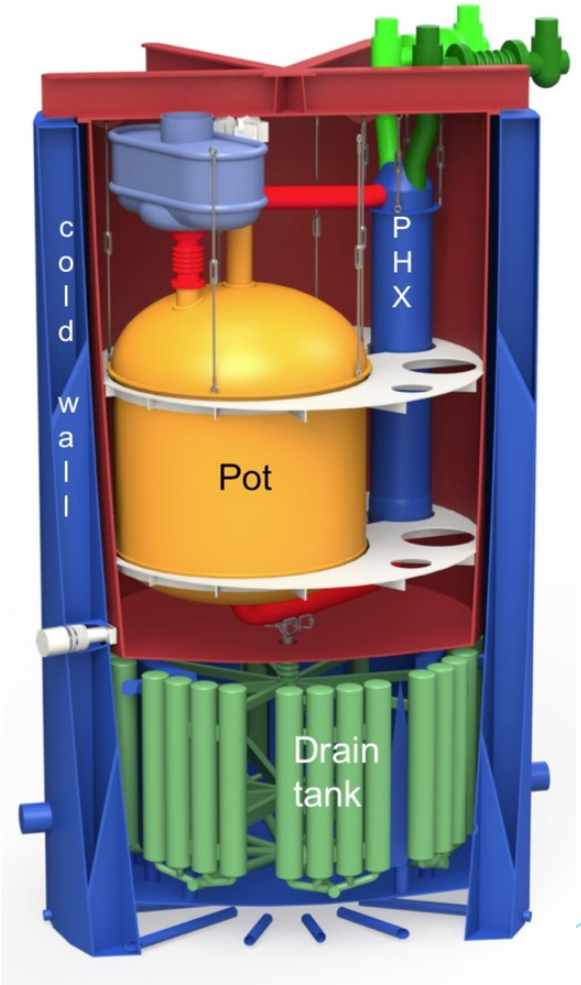
Small Modular Reactors

SMART	100 PWR	water	low	medium	high	limited; licensed	medium
NuScale	50 PWR	water	low	medium	high	minus; not licensed	medium
SMR-160	160 PWR	water	low	medium	high	minus; not licensed	medium
KLT-40	40 PWR	water	medium	medium	high	limited; licensed	medium
West 225	225 PWR	water	low	medium	high	minus; not licensed	medium
CAREM	27 PWR	water	low	medium	high	limited; licensed	medium

Thorium Molten Salt Reactor



ThorCon Can, and Drain Tank in Silo Cold Wall



ThorCon Molten Salt Reactor

- Hexagonal graphite logs used in reactor core to moderate neutron energies
- No reactor core excess reactivity and no control rods
- Plant load following accomplished by changing primary loop pump speed
- Neutron absorption in fertile thorium-232 and uranium-238 isotopes produces fissile uranium-233 and plutonium-239, respectively
- High temperature processing of salt fuel separates fission products from fissile materials

Antares Micro-Reactor Schematic

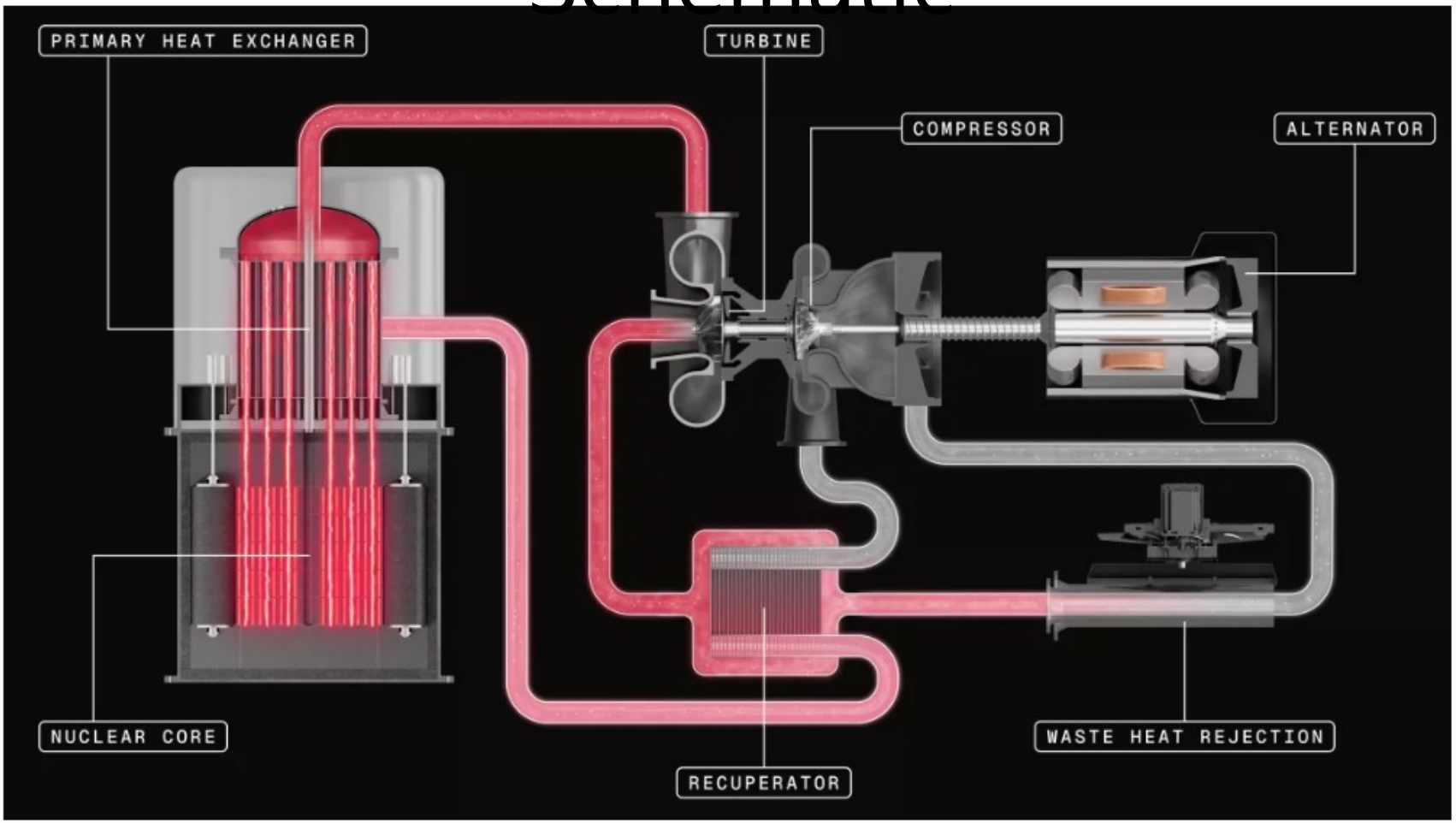
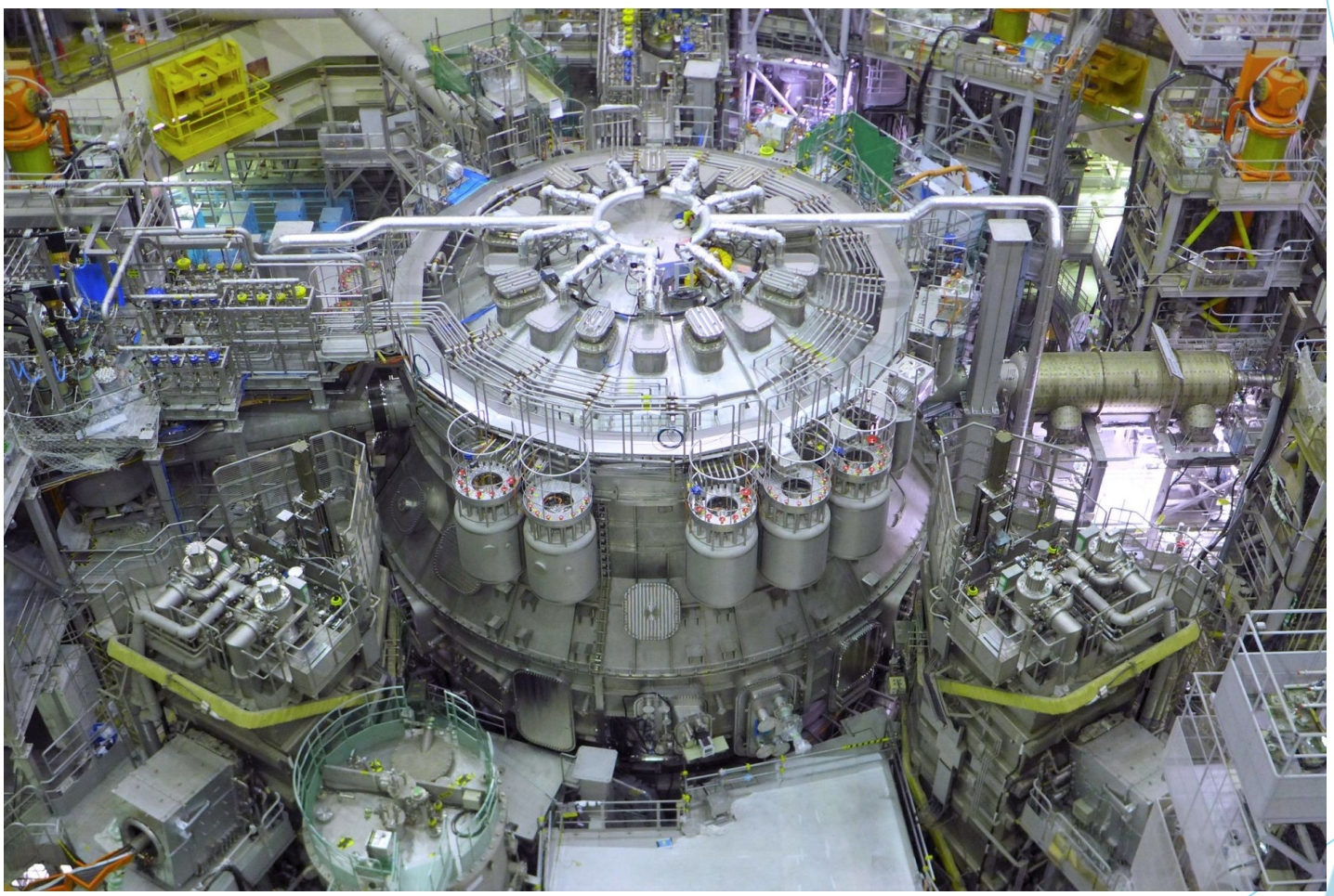
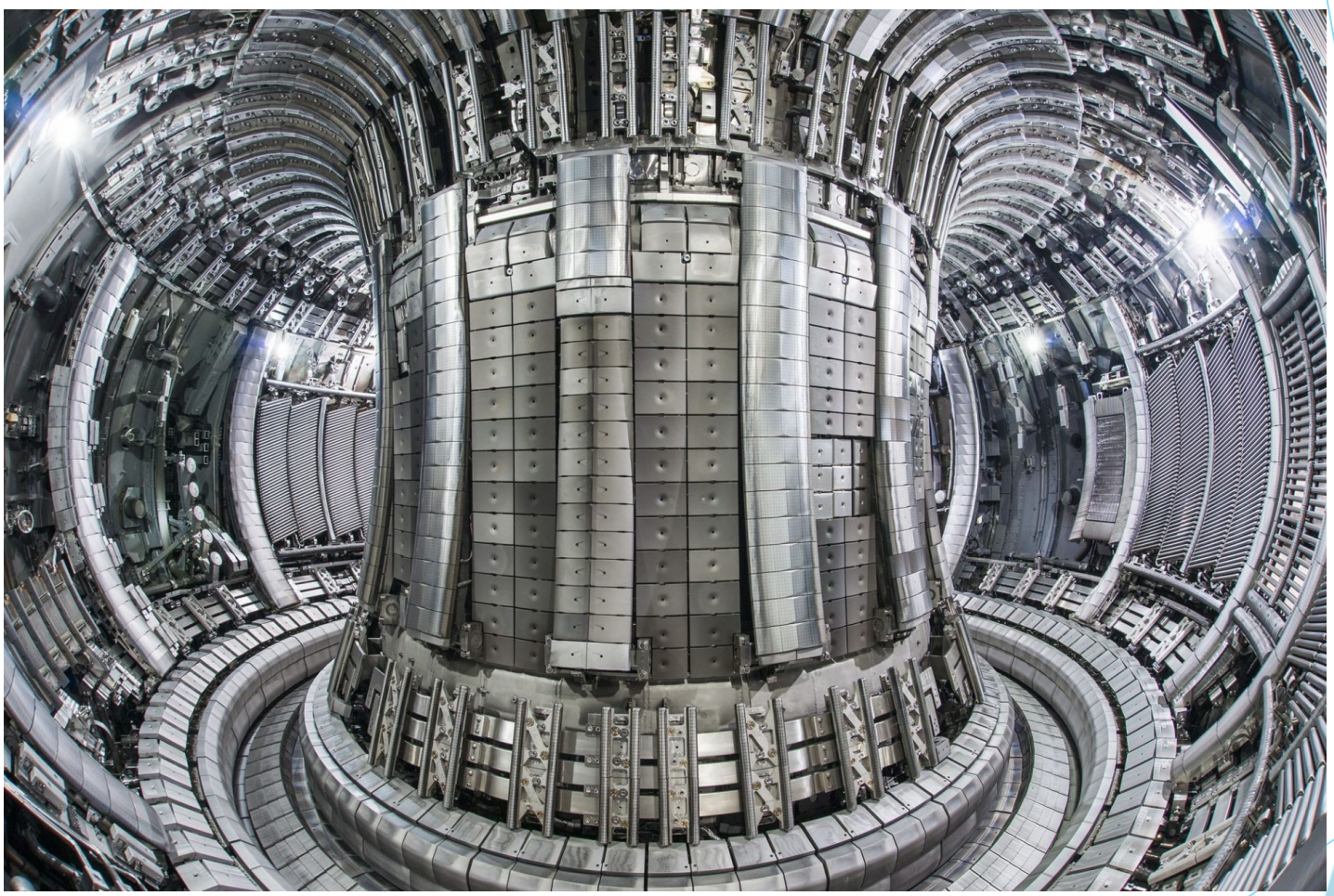


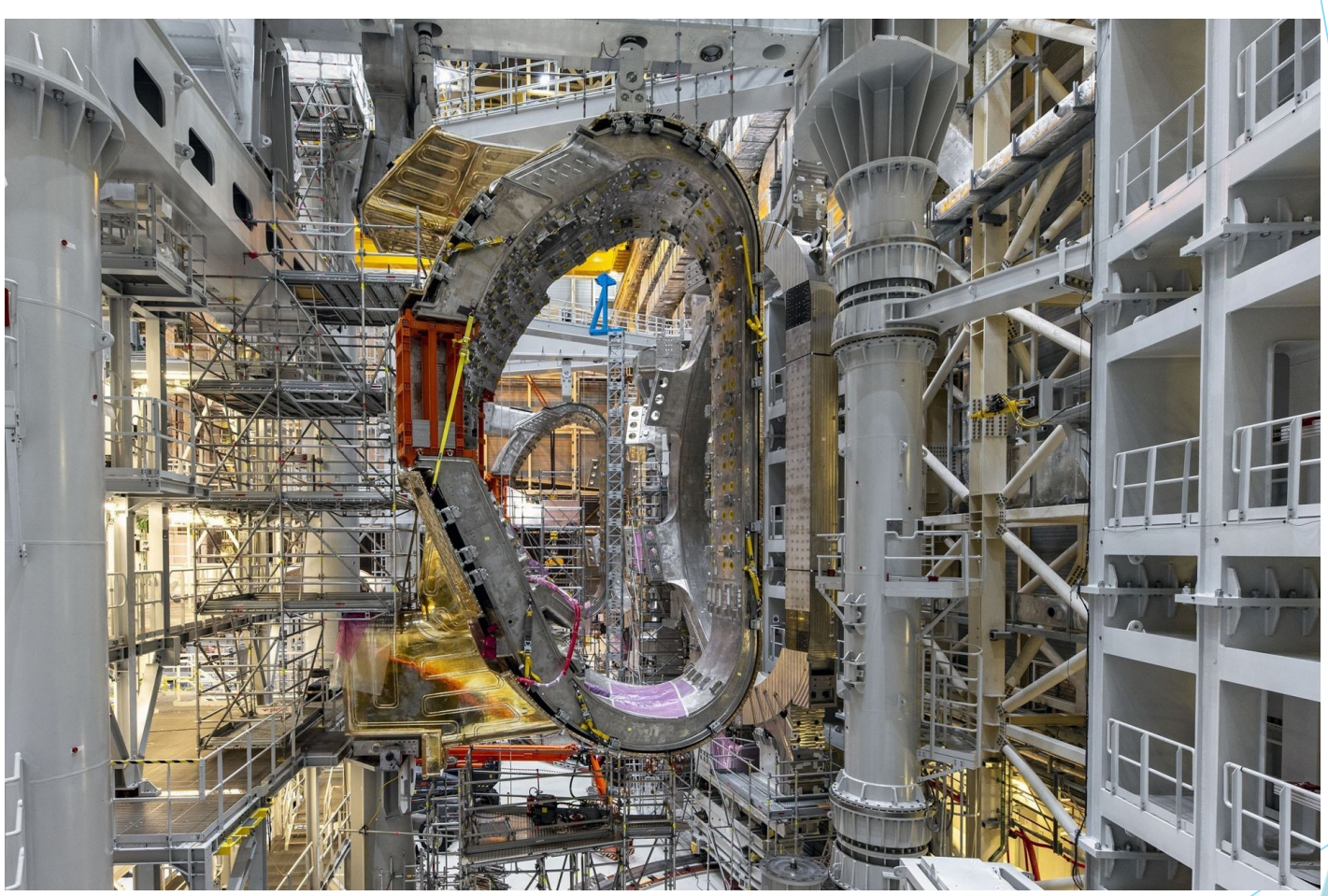
Diagram of the Antares reactor Antares



JT-60SA

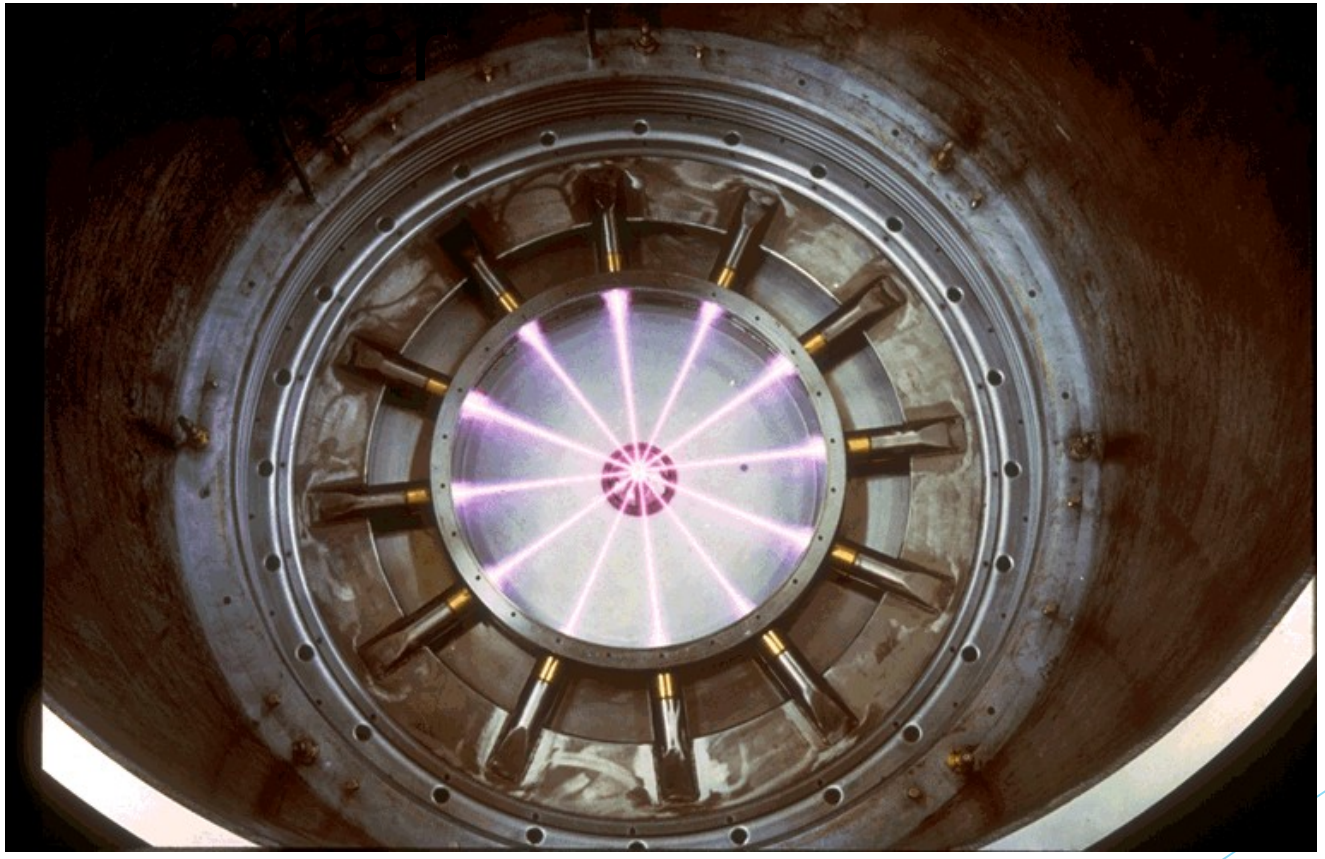


Joint European Torus (JET)

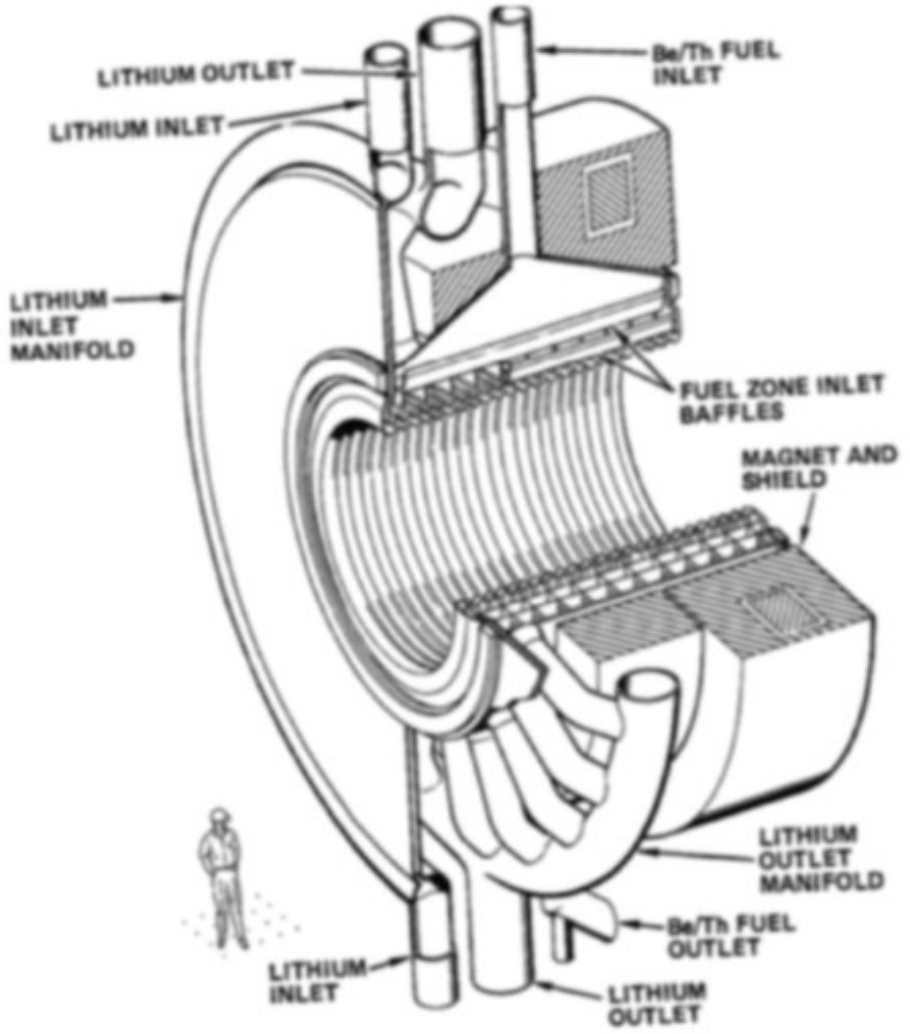


ITER

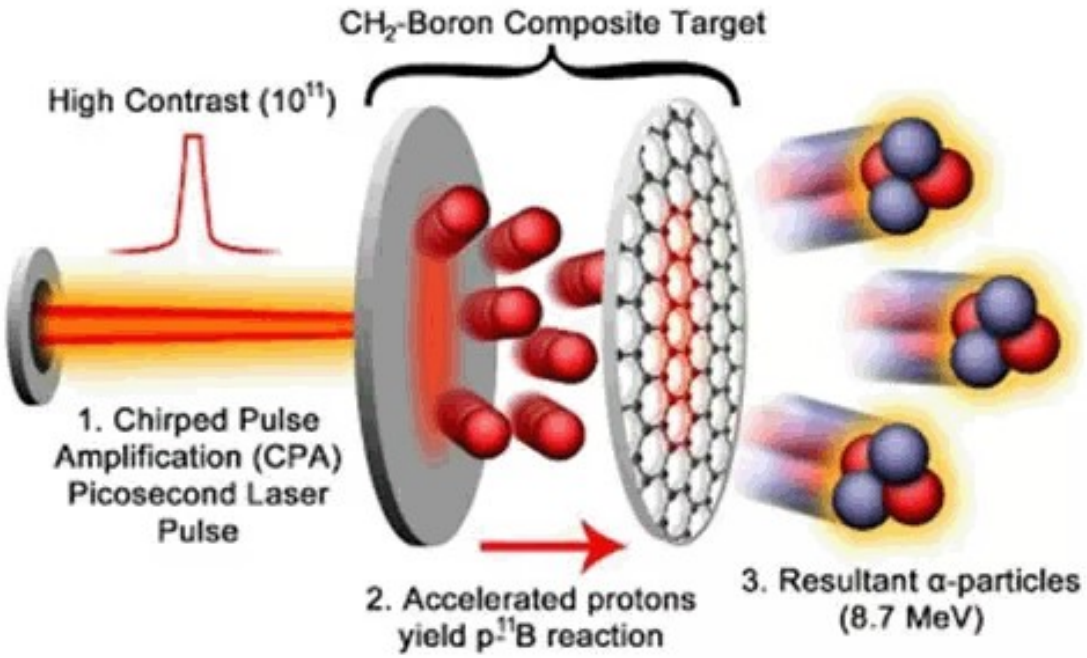
Inertial Confinement Target

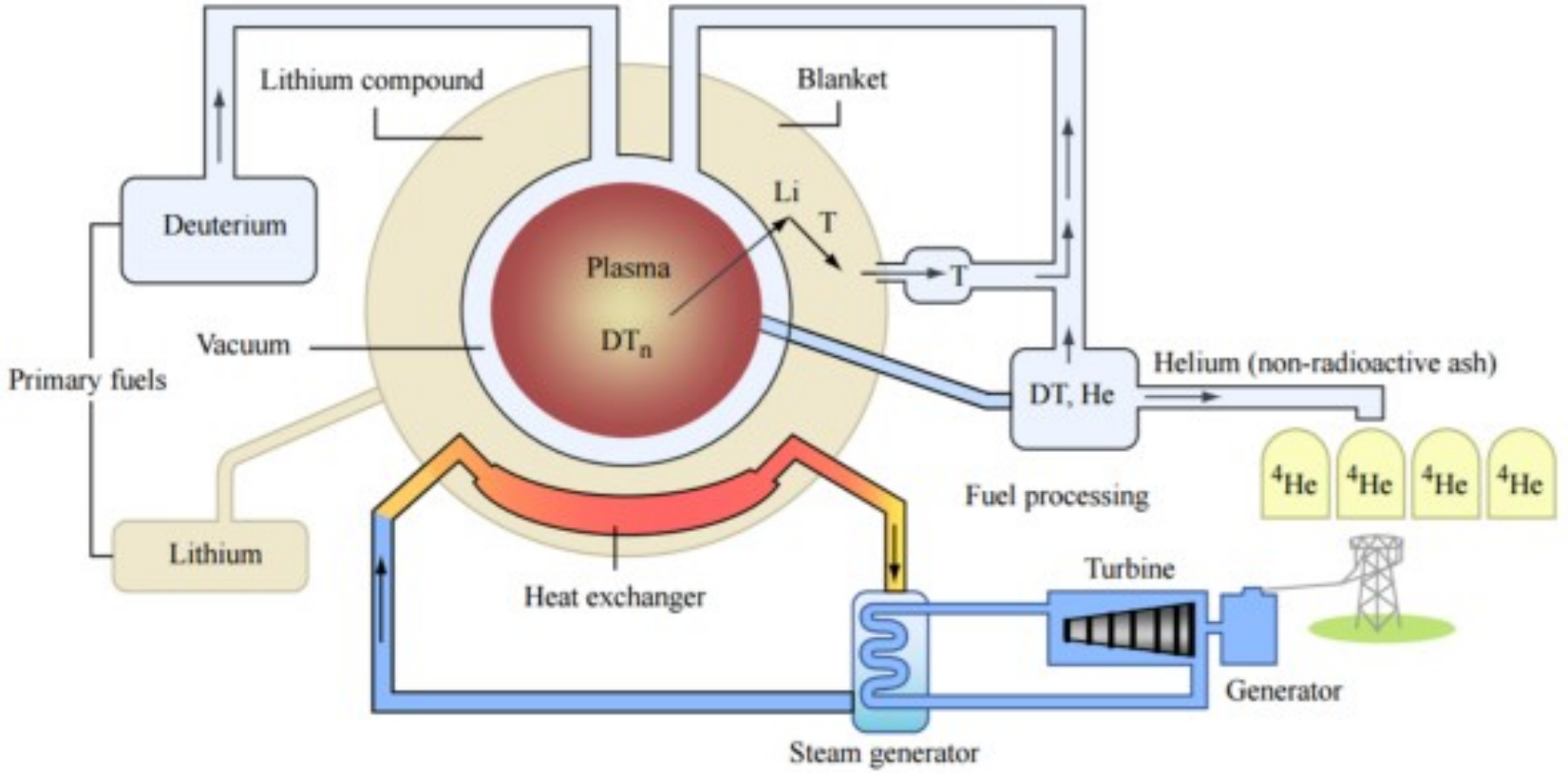


Schematic of Lithium Breeding Blanket Surrounding Fusion Reactor



Hydrogen-Boron Fusion


CH_2-Boron Composite Target
High Contrast (10^{11})
1. Chirped Pulse Amplification (CPA) Picosecond Laser Pulse
2. Accelerated protons yield $p^{11}B$ reaction
3. Resultant α-particles (8.7 MeV)


Lithium compound
Blanket
Deuterium
Li
T
Plasma
DT_n
T
Vacuum
Primary fuels
DT, He
Helium (non-radioactive ash)
^4He ^4He ^4He ^4He
Fuel processing
Lithium
Heat exchanger
Turbine
Generator
Steam generator